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Mine waste or future resource?

Integrating industrial ecology thinking into a mining project

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Abstract

Growing demand for natural resources coupled with declines in ore grades globally are increasing the environmental footprint of the extractive industry, in particular through higher energy and water consumption and waste generation. There are a variety of sustainability frameworks that have been designed for the mining industry and each of these define principles and strategies to improve the industry's sustainability performance. However, most of these frameworks are missing a key characteristic related to the fundamentally different nature of mining compared with other industrial activities: the mineral resource itself. An important contribution to sustainable development by mining projects is the way they manage to maximise value and minimise waste from ore deposits, each deposit having its own unique properties.

Industrial ecology (IE) is a multidisciplinary field of research that studies the flows and stocks of material and energy within society, and their impact on the environment, with the aim of designing more sustainable production and consumption systems. This thesis applies industrial ecology ideas and tools to the metal mining industry, and focuses on flows of mineralised material, observing the causes and consequences of mineral losses occurring at the mine site level.

The IE framework developed has three main levels of analysis. The first level focuses on mine waste management. Mine waste management practices were reviewed and assessed in terms of whether they inhibit or enable future mineral resource recovery, or any other value creation from the local mineralised material. A new Mine Waste Management Hierarchy 'reduce – reprocess – downcycle – dispose' was developed in accordance with principles of waste minimisation and value maximisation, and illustrated with examples from reported practices as well as academic research.

In order to connect better the mine waste management system with the rest of the mine's metabolism, the second level of the framework proposes a set of Material Flow Accounting (MFA) indicators, which provides a general view of the site's internal mineral flows. This set places a particular emphasis on quantifying mineral losses, which occur through different dissipative mechanisms, and with an evaluation on whether these losses are irreversible or potentially recoverable.

The MFA indicators have been applied on two case studies in Australia: the former gold and now abandoned mine, Mount Morgan in Queensland, and the copper mine, Mount Lyell in Tasmania. As both mine sites have had long histories, they have hosted several mining ventures whose performances have been assessed and compared using the MFA indicators. Comparisons of the different mining ventures at each case study site allowed for identifying the conditions for prolonging the life of mining operations and increasing mineral recovery, either from the ore deposit itself or by recycling mining waste. Such outcomes are desirable from a sustainability perspective in the sense that they take into account both the exhaustibility of a non-renewable resource and the need to minimise environmental impacts of mineral-rich waste material. The MFA results also allow for quantifying the consequences of unplanned and incomplete closures, long-term interruptions in operations and poor waste management, which have all contributed to exacerbating mineral losses.

The third and last level focuses on the role of governments in relation to the two case study sites. In particular, it was found that governments have a significant role to play, and this was demonstrated through the strengthening of environmental regulations over the past century, which has led to reduced mineral losses. However, the Queensland and Tasmanian governments' regulatory frameworks still could be improved in order to prevent or better control the consequences of premature closures of mining projects. This would require stronger links between the relevant environmental protection and mining state government departments. Using the Mine Waste Management Hierarchy as base principles for best practices in mine waste management, and using the MFA indicators to assess the performance of mining projects during the approval process could both inform policy-makers on potential ways to improve the current regulatory systems and help stimulate a positive change in mining practices.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

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Publications during candidature

Peer-reviewed papers:

- Lèbre, É. and G. Corder. 2015. *Integrating Industrial Ecology Thinking into the Management of Mining Waste.* Resources, 4, 765-786.
- Lèbre, É., G. D. Corder, and A. Golev. 2016. *Sustainable practices in the management of mining waste: A focus on the mineral resource.* Minerals Engineering, 107, 34–42.
- Lèbre, É., G. D. Corder, and A. Golev. 2017. *The role of the mining industry in a circular economy: a framework for resource management at the mine site level.* Journal of Industrial Ecology, 21, 3, 662–672.

AusIMM Bulletin article, co-authored:

- Corder, G. D., A. Golev, and É. Lèbre. 2016. *The contribution of mining to the emerging circular economy*. The AusIMM Bulletin. https://www.ausimmbulletin.com/feature/the-contribution-of-mining-to-the-emerging-circular-economy/

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- Lèbre, É. 2015. ‘Mine waste or potential future resource: integrating Industrial Ecology thinking into a mine project’, in World Resources Forum Asia□Pacific, Wealth from Waste: Resource Productivity and Innovations, 1-3 June 2015, Sydney, Australia.
- Lèbre, É. 2015. ‘Mine waste or potential future resource: integrating Industrial Ecology thinking into a mine project’, in ISIE conference 2015: Taking Stock of Industrial Ecology, 7-10 July 2015, University of Surrey, Guildford, UK.
- Lèbre, É. 2015. ‘Forging a sustainable future in mining: a new approach to the management of mining waste’, in SMI RHD conference 2015, 4 December 2015, Sustainable Minerals Institute, The University of Queensland, Brisbane, Australia.
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- Lèbre, É. 2016. ‘The role of the mining industry in a circular economy: a framework for resource management at the mine site level’, in Life-of-Mine conference 2016, 28-30 September 2016, Brisbane, Australia.
- Lèbre, É., Golev, A. 2016. ‘The role of the mining industry in a circular economy: a framework for resource management at the mine site level’, in The International Society for

Industrial Ecology (ISIE) Joint 12th Socio-Economic Metabolism section conference and 5th Asia-Pacific conference, 28-30 September 2016, Nagoya, Japan.
- Lèbre, É, Corder, G and Golev, A 2017. 'Towards sustainable practices in the mining industry - material flow indicators to model a metal mine's metabolism and inform policy-making', in ISIE-ISSST 2017: Science in Support of Sustainable and Resilient Communities, 25-29 June 2017, Chicago, Il, USA.

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Author Artem Golev	Conception and design (10%) Analysis and interpretation (10%)

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Research Involving Human or Animal Subjects

No animal or human subjects were involved in this research.

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industrial ecology, mining waste, material flow analysis (MFA), waste management, sustainable resource use, mines and mineral resources

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List of abbreviations

AMD	Acid Mine Drainage
CMT	Copper Mines of Tasmania
DNRM	Department for Natural Resources and Mining
DEHP	Department of Environment and Heritage Protection
EE	Eco-Efficiency
EPA	Environment Protection Authority
EIS	Environmental Impact Statement
IE	Industrial Ecology
IS	Industrial Symbiosis
ICMM	International Council on Mining and Metals sustainability
LPSDP	Leading Practices in Sustainable Development Program
LCA	Life Cycle Assessment
MFA	Material Flow Accounting
MWM	Mine Waste Management
MWMH	Mine Waste Management Hierarchy
MRT	Mineral Resources Tasmania
MEI	Minerals Engineering International
MMSD	Mining, Minerals, and Sustainable Development
MLMRC	Mount Lyell Mining and Railway Company
MFP	Multifactor Productivity
3Rs	Reduce, Reuse, Recycle
STR	Sandstone Gully Tailings Reprocessing
SIS	Seepage Interception System
7QS	Seven Questions to Sustainability
STAF	Stock and Flow (project)
SWOT	Strengths, Weaknesses, Opportunities, Threats
SDAC	Sustainable Development Advisory Council
WMP	Waste Management Plan

Material Flow Accounting indicators

TP	Total Production
TPW	Total Production from Waste

TMP Total Material Processed

TMM Total Material Moved

NWG Net Waste Generation

MLNW Mineral Losses to New Waste

TMLW Total Mineral Losses to Waste

ME Material-Efficiency

EI Extraction Inefficiency

IML-D Irreversible Mineral Losses through Dumping

IML-AMD Irreversible Mineral Losses through AMD

RLB Resource Left Behind

NAI New Area Impacted

1. Introduction

1.1. Problem statement

The metal mining industry is a key player in the global natural resource exploitation and it makes an important contribution towards sustainable development goals. It extracts a non-renewable resource out of the ground, while consuming extensive amounts of other resources such as water and fossil fuels, and degrading others such as local ecosystems and land. The continuously growing global demand for metals causes declining ore grades, which in turn result in increased energy requirements (Norgate, Jahanshahi & Rankin 2007) and water use (Norgate & Lovel 2004) in mining processes. Because it is becoming more and more difficult to access and extract the target minerals, waste generation and the associated environmental impacts of waste disposal also follow upward trends and often dominate mining legacies (Lottermoser 2010; Mudd 2009).

In this context, this thesis asks what would be the conditions for a sustainable exploitation of mineral resources to be achieved at the mine site level, and more generally, how a mine could contribute more effectively to sustainable development.

Industrial ecology is a relatively young field of research that studies "the flows of materials and energy in industrial and consumer activities, the effects of these flows on the environment, and the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources" (White, R 1994). Offering a systemic and multidisciplinary perspective, it has been often viewed as the science of sustainable development (e.g. Basu & van Zyl 2006) and can potentially supply an appropriate framework to think the above interrogations.

The industrial ecology concept compels the practitioner to study the opportunities to 'close the loop' and view waste as a potential resource, in the aim of minimising primary resource consumption as well as waste generation. In the mining context, mineral and mineralised material flows and stocks characterise the metabolism of a mine site. The conversion from a mineral locked in the ore body to a refined metal is subject to inefficiencies – both technical and non-technical. As a result, a high amount of the minerals targeted for extraction ends up in the waste stream. In addition, mine waste deposits are associated with one of the most serious environmental problems occurring in mine sites: heavy metals and acid generation and leakage through a phenomenon called acid mine drainage (AMD). Interestingly, the toxicity of this leakage is partly due to the presence of un-extracted sulphide minerals in the waste stream. There is therefore a correlation between inefficiencies in the extraction process and the environmental footprint of the mine site.

This thesis investigates the opportunities to recover minerals and more generally create value out of mining waste. It studies how a preventive, recovery-oriented mine waste management could contribute to enhancing the recovery of mineral resources while reducing the environmental footprint related to waste disposal.

1.2. Research questions and objectives

Based on this context, a main research question was formulated:

How could a preventive, recovery-oriented mine waste management system based on the concept of industrial ecology, which would view waste as a potential future resource, contribute to improving the sustainability credentials of a metal mine?

Secondary questions develop this first question further and provide a general structure to the project:

a) What main characteristics should this mine waste management system follow?
b) How does such a change in waste management practices improve the overall metabolism of a mine site, and how can this improvement be measured?
c) What are the main actors to stimulate a positive change, and what kind of external incentives could help implement identified solutions into practice?

Each secondary research questions corresponds to a different level in the framework that is developed for this thesis. While research question a) focuses on mine waste management, research question b) seeks to integrate waste management within the temporal and organisational boundaries of a mine. Research question c) expands the view further by looking at influential actors, particularly those situated outside of the extractive industry. Although a diversity of actors play an important role in influencing mining practices (these actors are presented in section 4.1.2), the answer to question c) focuses mainly on policy incentives. Figure 1.1 below allows to visualise these three main levels, noting that level for research question b) is subdivided into the mining project and the mine life cycle. These two distinct elements will be further presented in Chapter 4.

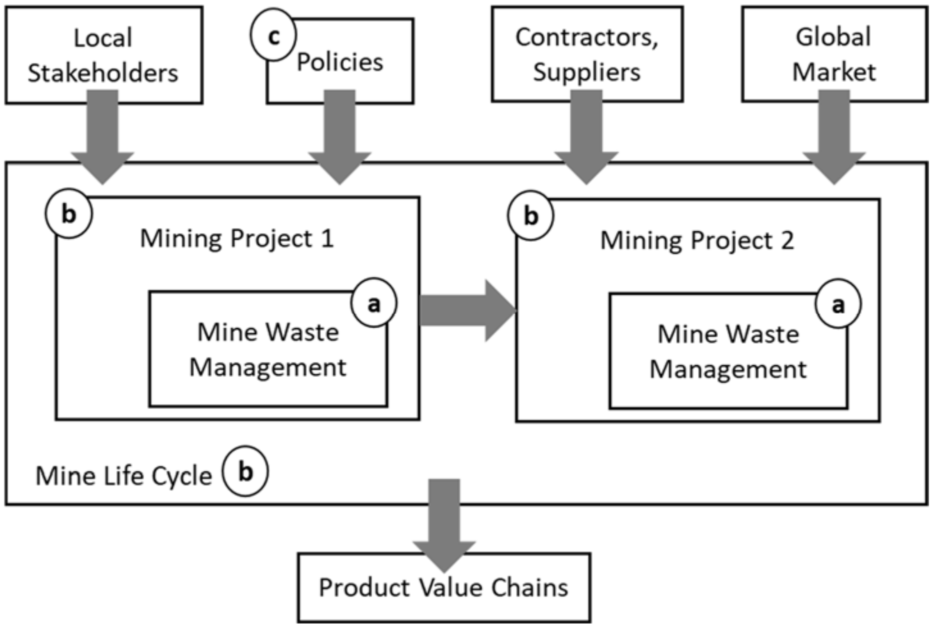

Figure 1.1: Levels of analysis of the thesis, and their correspondence to the three secondary research questions

To answer these questions, a set of objectives for this thesis is defined below:

i. From a review of the literature, identify key shortcomings of existing mining sustainability frameworks that will serve as basis for determining the contribution industrial ecology can make and settle the scope of this thesis.

ii. Develop and apply an industrial ecology-based framework for the thesis that aims at addressing these key shortcomings. This framework is centred on mine waste management and sees waste streams as a key component to study the inefficiencies of a mine site's internal metabolism;

iii. As part of the framework, define the characteristics of a mine waste management system integrated within mine plans and designed to maximise overall resource extraction and minimise final disposal of reactive waste. This objective leads to establishing a definition of what a 'preventive, recovery-oriented mine waste management' is, and support the use of this expression in the main research question;

iv. As part of the framework, select, adapt and apply an existing industrial ecology modelling tool in order to map the flows of minerals and mineralised material at the mine site level. In particular, the tool should allow for quantifying the different kinds of mineral losses and demonstrate its applicability and effectiveness through two case study mine sites in Australia;

v. As part of the framework, use case study findings to make policy recommendations to implement identified changes into practice;

vi. Demonstrate that the recommended changes in mine waste management, mine planning and mining regulations would be a significant step in favour of a more responsible exploitation of mineral resources.

Figure 1.2 shows how the different objectives fit in the thesis chapters.

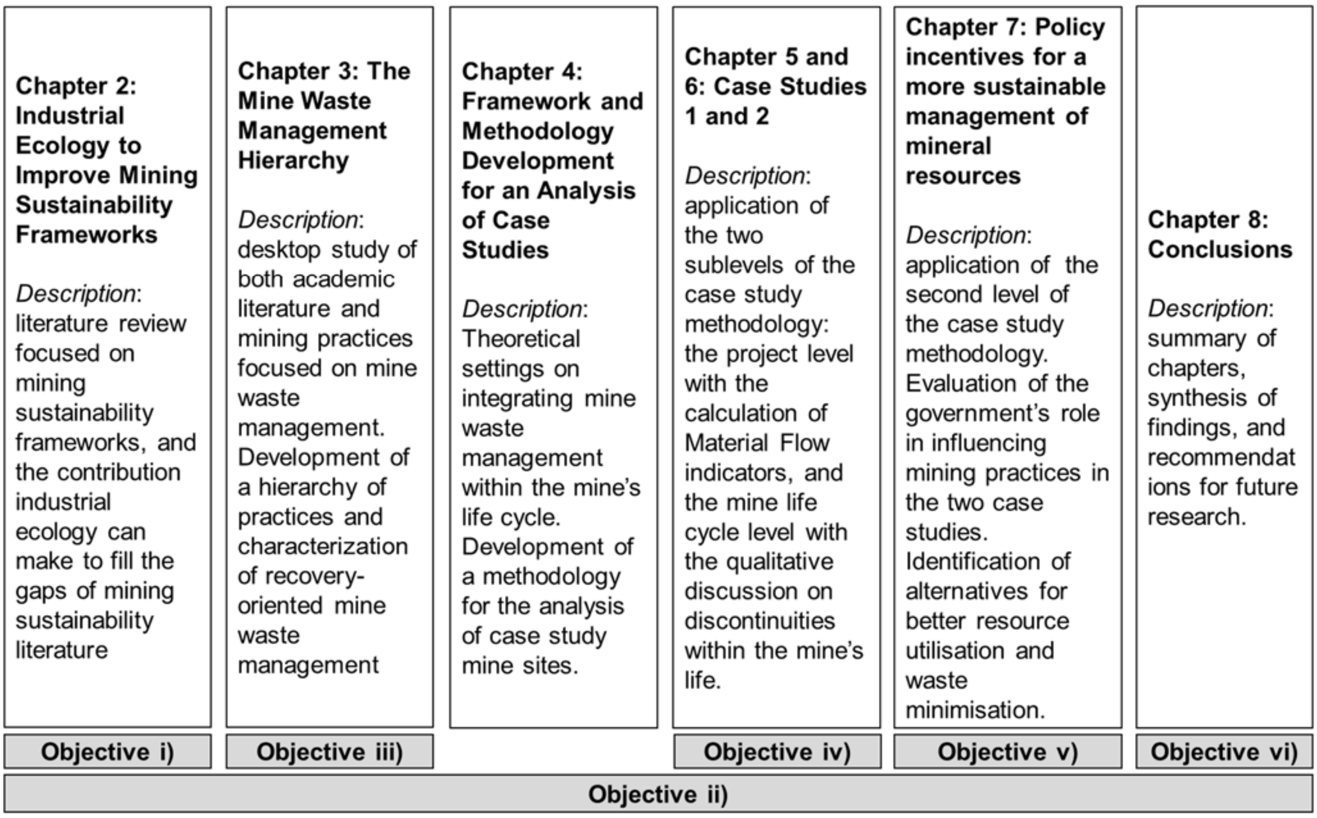

Figure 1.2: Main thesis structure with positioning of the objectives in corresponding chapters

2. Industrial ecology to improve mining sustainability frameworks

This literature review chapter provides the background to explore the main research question. It first critically reviews existing mining sustainability frameworks, evaluating their ability to encompass all relevant dimensions, measure performance and progress, and provide guidance to implement solutions into practice. Then, section 2.2 presents the industrial ecology field, discusses how equipped it is to address identified limitations from mining sustainability frameworks, and reviews current applications to the mining sector.

2.1. Sustainability frameworks for the mining industry

There are numerous sustainability frameworks applicable to the mining industry, as well as a multitude of interpretations of sustainable development in mining. A review of frameworks applied to mining and relevant to the research topic in this thesis is presented in this introductory section of the literature review. The purpose here is not to provide a comprehensive list but rather to critically examine some of the most recognized frameworks, identify what is currently missing in sustainability research in mining and more generally present the context in which this thesis was written.

2.1.1. Main sustainability frameworks

2.1.1.1. The triple bottom line and the five capitals framework

To define sustainability in the mining context, some authors have used the traditional triple bottom line, also called the three pillars of sustainability - profit, people and planet – as shown in Table 2.1.

Table 2.1: Some definitions of sustainable development in the mining industry

Laurence et al. (2011), p8	“In the minerals sector, sustainable development means that investments in minerals projects should be financially profitable, technically appropriate, environmentally sound and socially responsible”
James (1999)	“Miners can achieve sustainable development by embracing the social, environment and economic pillars” (Laurence et al. 2011)

Norgate and Haque (2010)	“The sustainability of the minerals industry is about managing [the material] cycles in ways that maximise the value to society while minimising negative impacts, be they economic, social or environmental”
Hilson and Murck (2000)	“Sustainable development in the corporate mining context requires a commitment to continuous environmental and socioeconomic improvement, from mineral exploration, through operation, to closure.”
Labonne (1999)	“Offsetting of reinvesting the benefits from the depleting mineral asset” (Laurence et al. 2011)

Other frameworks have used more than three sustainability dimensions. Some have added the governance sphere to the triple bottom line, making it a four dimensional issue (MMSD 2002a). The guide made by the Leading Practices in Sustainable Development Program (LPSDP) for the mining sector (Laurence et al. 2011) proposes five dimensions: economy, environment, community, safety and efficiency.

The five capitals framework is another framework, which distinguishes the natural capital from the anthropogenic capital, and divides the latter into the financial, social, human and physical capitals (see Figure 2.1)(Corder 2015; Porritt 2003). It has been often used in the mining context as a qualitative and descriptive framework. Limpitlaw (2006) used the five capitals framework for his assessment of small scale mining in Africa. Other applications include the work from Moran, Franks and Sonter (2013). This paper uses the five capitals as a basis to develop and measure indicators. Horsley et al. (2015) and Brereton and Pattenden (2007) on the other hand use the five capitals in a qualitative organising framework to analyse a particular topic related to mining. Martinez and Franks (2014) present case studies where the five capitals framework was applied by the mining company. Porritt (2003) provides a good description of the general framework and how it is to be used.

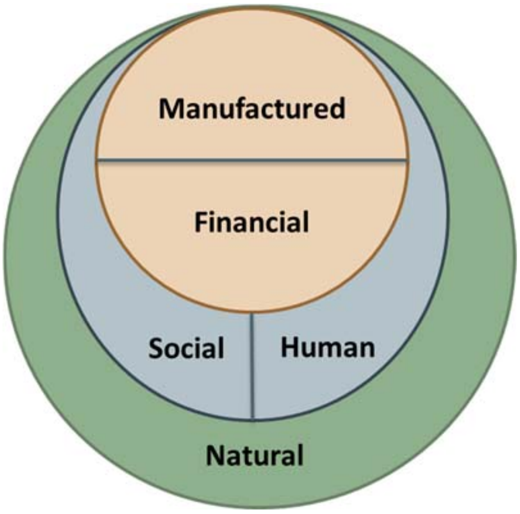

Figure 2.1: The five capitals

The use of these two frameworks raises the question of 'strong' versus 'weak' sustainability (Moran & Kunz 2014; van Berkel 2000): strong sustainability requires that there is only a limited trade-off between the five capitals. It aims at improving all capitals together, not allowing any of them (notably the natural one) to decrease over time. Weak sustainability on the other hand allows a trade-off that may result in one capital to decrease at the expense of the other capitals. Two of the papers on the five-capital framework mentioned above (Brereton & Pattenden 2007; Moran, Franks & Sonter 2013) include a discussion on weak versus strong sustainability in mining. Moran, Franks and Sonter (2013) argue that a transfer between the natural capital and the anthropogenic capitals will necessarily occur in mining, hence only weak sustainability can be sought. This point of view is also visible in the definition proposed by Labonne (1999) (see Table 2.1). Brereton and Pattenden (2007), Kirsch (2010) and Hilson and Murck (2000) on the other hand, maintain that accepting this view provides license to environmental degradation, which should remain unacceptable.

2.1.1.2. The International Council on Mining and Metals sustainability principles

According to McLellan et al. (2009) the International Council on Mining and Metals' (ICMM) 10 principles and the Seven Questions to Sustainability are two of the most promising mining sustainability frameworks and have the potential to guide mine planners towards better performances.

The ICMM's 10 principles for sustainable development (presented in Table 2.2) were defined in 2003 and since then member companies are committed to implement and measure their performance in relation to these principles. In 2015 the ICMM brings together 21 global mining corporations and 35 mining and commodity associations (ICMM 2015a).

Table 2.2: ICMM's 10 sustainable development principles (ICMM 2015b)

	10 Principles	Correspondence to 5 capitals
1	Implement and maintain ethical business practices and sound systems of corporate governance	Social
2	Integrate sustainable development considerations within the corporate decision-making process	All
3	Uphold fundamental human rights and respect cultures, customs and values in dealings with employees and others who are affected by our activities	Human, Social
4	Implement risk management strategies based on valid data and sound science	All
5	Seek continual improvement of our health and safety performance	Human
6	Seek continual improvement of our environmental performance	Natural
7	Contribute to conservation of biodiversity and integrated approaches to land use planning	Natural
8	Facilitate and encourage responsible product design, use, re-use, recycling and disposal of our products	Natural, Manufactured
9	Contribute to the social, economic and institutional development of the communities in which we operate	All anthropogenic capitals
10	Implement effective and transparent engagement, communication and independently verified reporting arrangements with our stakeholders	Social

The 10 principles cover and go beyond the 3, 4, or 5 sustainability dimensions presented previously, as they also identify other important aspects to the contribution of mining to sustainable development (ICMM 2015c). In particular, the stakeholders that may be affected are named: employees (principle 3), the local community (principle 9), the country where mining occurs and its government (principle 1), society as a whole as consumer of metal containing products (principle 8). The 10 principles also therefore show that there are different geographic scales to consider, which, as pointed out by Moran and Kunz (2014), vary from the local level of ‘operating sustainably’ to the global concept of sustainable development.

Despite the fact that many principles are to be implemented at a local scale, nearly all principles include the integration of the mining activity into the bigger system: they underline the importance of involving the stakeholders, creating positive value for the local communities and nations, sharing of information and transparency in order to encourage the dissemination of good practices. Principles 5 and 6 emphasize the need for continual improvement, which provides a time dimension and an evolutionary perspective to the framework.

Principles 6 and 8 offer a particular focus on waste management. However, principle 6 is primarily focused on mitigating the environmental impacts of waste generation, with a particular emphasis on storing waste in a safe way and rehabilitating the site after closure. Here mine waste is therefore only seen as an environmental problem to be minimized, not as a potential future resource.

Principle 8 connects the mining industry to the downstream production and involves it in the efforts towards closing material cycles. This principle includes the understanding of a material’s life-cycle impacts and highlights the need for an integrated materials management across value chains. Although this principle is important, one may question how the mining industry can take part in strategies that aim at reducing material intensity and therefore the need for primary metals.

2.1.1.3. The Seven Questions to Sustainability framework

The Seven Questions to Sustainability (7QS) framework is a result of the Mining, Minerals, and Sustainable Development (MMSD) research project, and is another framework often used by the mining industry (although the ICMM principles are the most commonly used according to McLellan et al. (2009)). It was meant to be a guide for decision-makers to help them assess the performance of mineral projects in terms of sustainability. The topics covered by the seven questions are Engagement, People, Environment, Economy, Traditional and Non-Market Activities, Institutional Arrangements and Governance, and Synthesis and Continuous Learning (see Table 2.3).

Table 2.3: The Seven Questions to Sustainability (IISD 2002)

	Topics	Questions
1	Engagement	Are engagement processes in place and working effectively?
2	People	Will people's well-being be maintained or improved?
3	Environment	Is the integrity of the environment assured over the long term?
4	Economy	Is the economic viability of the project or operation assured, and will the economy of the community and beyond be better off as a result?
5	Traditional and Non-market Activities	Are traditional and non-market activities in the community and surrounding area accounted for in a way that is acceptable to the local people?
6	Institutional Arrangements and Governance	Are rules, incentives, programs and capacities in place to address project or operational consequences?
7	Synthesis and Continuous Learning	Does a full synthesis show that the net result will be positive or negative in the long term, and will there be periodic reassessments?

From each of these questions and topics, the framework proposes an 'ideal' answer, as well as examples of indicators and metrics that can be directly used or adapted to evaluate the company's success in addressing the seven questions (MMSD 2002b).

Most of the 7QS overlaps with the ICMM 10 principles and the 5-capital framework. However, the proposed indicators and metrics go beyond a definition of sustainability and make a step forward to a practical implementation.

2.1.2. Limitations of current sustainability frameworks

The Global Compendium of Sustainability Indicators Initiatives includes more than twenty other frameworks that can be used to assess the sustainability performance of mining (IISD 2012). Academic publications proposing similar frameworks are growing in number as well (Fonseca, McAllister & Fitzpatrick 2013). There is therefore not a lack of frameworks available and Weber (2005) deems an attempt to reconcile the various approaches would be unsuccessful. Furthermore, Fonseca, McAllister and Fitzpatrick (2013) question their effectiveness and underline the need to assess a framework's ability to fulfil its purpose.

2.1.2.1. The weak version of sustainability

Moran and Kunz (2014) commented on the potential of the triple bottom line, the five capitals, the ICMM principles and the 7QS frameworks. The authors acknowledged that decomposing the definition of sustainability in mining into several bullet points is useful in the way that it allows for identifying the key characteristics of a multifaceted problem. However, one is then exposed to the risk of dealing with the separate smaller issues while failing to identify a potentially stronger central solution. As Moran and Kunz (2014) point out, improvement in a list of indicators does not necessarily mean an improvement of the overall system. The review by McLellan et al. (2009) reaches the same conclusion that current frameworks are not integrative. Fonseca, McAllister and Fitzpatrick (2013) confirm that the 7QS, while providing guidance to analyse trade-offs and synergies in the seventh question, do not propose practical ways to measure them.

The frameworks presented above therefore do not seem to provide enough guidance on ways to implement the strong version of the sustainability definition. This shows a lack of understanding of the interconnectedness between the different sustainability dimensions.

2.1.2.2. Overlooking the non-renewability of the resource

Fonseca, McAllister and Fitzpatrick (2013) evaluated the performance of five different sustainability frameworks for the mining industry, namely the global reporting initiative's mining and metals sector supplement (GRI 2011), the framework developed by Azapagic (2004), the one developed by Basu and Kumar (2004), the one developed by the mining association of Canada (MAC 2016), and the 7QS. The authors concluded that, overall, the five frameworks tend to have a retrospective and siloed approach, which does not allow addressing the question of sustainability in a comprehensive way. In particular, the scarcity of mineral resources and the mining legacies - some of the most important challenges in mining - are not addressed sufficiently.

This argument is supported by the authors of the Leading Practices in Sustainable Development Program (LPSDP) mining guide (Laurence et al. 2011) who added an efficiency dimension to their sustainable mining practices model. Laurence et al. (2011) state that researchers have approached the subject of the exhaustibility of the mineral resource as a depleting asset from a macro level, while there is a need to focus on the micro level. In other words, sustainable resource management, defined as a resource management that fulfils both current and future societal needs, also needs to be addressed at the mine site level. Ayres, Ayres and Råde (2002, p. 32) confirm that the current economic models used in designing a mine project “do not take into account energy or material resource depletion or thermodynamic constraints”.

Some of the studies on resource depletion do not recognise it as an immediate threat. There is an ongoing debate about whether abiotic resource depletion rate is becoming critical or not. Authors like Gordon, Bertram and Graedel (2006) and Allwood et al. (2011) evaluate that primary resource stocks will be able to meet future demand for several decades, although Allwood et al. (2011) points out that these calculations are subject to high uncertainties. On the other hand, Meadows, Randers and Meadows (2005), supported by Dudka and Adriano (1997) and Norgate and Jahanshahi (2010) assessed that the issue required urgent action. However, all authors seem to agree that human and natural limitations in resource extraction are likely to arise in the relatively short term. The decrease in availability and accessibility of minerals in the ground, visible in the global trends of ore grade decline (Mudd 2009), is the main driver of increased energy use (Norgate, Jahanshahi & Rankin 2007), water consumption (Norgate & Lovel 2004) and more generally environmental footprint.

This efficiency dimension is specific to the mining industry. In other industrial sectors resource efficiency - or resource productivity - refers to the efficient use of material resources such as infrastructure, energy and water (Hammer & Somers 2014). In the mining industry, Laurence (2011) argues that it should also include the resource being extracted. It is critical to optimize and enhance resource extraction while still taking into consideration the overall resource efficiency.

The efficiency dimension is overlooked by the frameworks presented earlier. It is absent in the 7QS. It is somewhat present in Principle 8 of the ICMM principles, which highlights the need for product recycling and reuse, although this addresses improvement further down the value chain, not mining operations The five-capital framework does consider the natural resource as a part of the natural capital, however applications of this framework have not properly taken into account this aspect (Moran & Kunz 2014).

2.1.2.3. Economic viability and resilience as a core sustainability dimension

Economic viability is an important sustainability dimension in the frameworks presented above (the economy/profit bottom line, question number 4 in the 7QS). The MMSD research project (MMSD 2002a) highlighted economic viability as the first of nine main challenges the mining industry is facing. The practical reality of this challenge is described by Laurence (2011), who analysed one thousand mine closures happening in a 30-year period, and observed that 75% of them closed prematurely, most of the time as a result of economic difficulties. These economic difficulties can come from the mining industry’s boom-bust cycle dynamic, which follows the fluctuation of commodity prices (Shandro et al. 2011), or from other sources of uncertainty that result in higher operating costs, e.g. uncertainties related to the composition of the ore body (Laurence 2011).

Consequences of premature closures affect all the other sustainability dimensions. At the human and social levels, employees lose their jobs, and discontinuance in the mine’s operations will compromise support to local communities. The financial actors lose their investments as mining companies may be unable to pay back their debts. The infrastructure built around and for the mining project (rail lines, process plant, water treatment plant, power plant etc.) may be abandoned with lack of maintenance, making it unusable in the future.

Unplanned closures are particularly detrimental for the natural capital, because rehabilitation and environmental reclamation might have been poorly addressed due to lack of time and financial means. Furthermore, a premature closure results in mining operations ending before all the economic resource has been extracted. Because the mine plans are discontinued and no alternative plans are developed, what is left of the resource is most likely sterilised, that is to say rendered uneconomic to extract. In parallel with this, the various material displacements occurring during mining activities would have exposed some of the unrecovered minerals, which, in contact with air and water, may contribute to the phenomenon of acid mine drainage, i.e. the leakage of dissolved metals in acid into the environment.

On the other hand, prolonging mining operations until all economic resources are recovered, could provide additional economic benefits. Completing resource extraction from currently operating mines would reduce the requirement for new mine openings, that is, for exposing and exploiting undeveloped ore deposits. Mine openings are characterized by a significant and mostly irreversible disturbance to the local environment (Lechner et al. 2015), and it seems therefore worth—under certain conditions—prolonging current operations rather than starting new ones on green fields (Weber 2005).

After a premature closure, mineral losses through resource sterilisation can potentially partially be reversed if a new mining project commences. However, the discontinuation in activities would require a higher capital investment from the new company, and irreversible mineral losses through uncontrolled acid mine drainage from exposed material may have occurred in the meantime.

The seriousness of the issue of economic viability receives little attention in current sustainability frameworks, perhaps because it is assumed that the economic bottom line is fully considered by companies, while environmental and social dimensions may not be part of the corporate strategy.

As a step forward in addressing this issue, Moran and Kunz (2014, p. 6) proposed a maturity framework for mining operations where the most advanced stage of maturity is “adaptable and resilient”, ‘adaptability’ being the flexibility in operating under external pressures, ‘resilience’ being the ability to ‘respond to a shock and return to a previously acceptable or good new operating state’. Adaptable and resilient mining operations remain economically viable until the end of the mine plans. This relates to another meaning of sustainability expressed by Laurence (2011), which connects with the original meaning of the word ‘sustain’: the ability to sustain mining operations in time.

The time perspective is essential in mining. Due to the non-renewability of its feedstock it is physically impossible to prolong a mining activity indefinitely. However, mine operations can be prolonged and Laurence's results show that there is a significant potential for improvement.

The challenge of economic viability is therefore essential in a sustainable resource management strategy. Resource sterilisation does not only occur in cases of premature closure. Laurence et al. (2011) describes an extractive strategy called high-grading, where high-grade material is selectively mined and the rest of the ore body is left behind. The medium or low-grade material that would have been economic to mine together with the high-grade one may be uneconomic on its own. This type of short-term extractive strategy caused by financial drivers can result in a "planned" or "voluntary" premature closure.

2.1.3. Summary of findings

There are numerous frameworks built to assess the mining industry's contribution to sustainable development, and that attempt to define what sustainability means in a mining context. Constructive criticisms of these frameworks focus on evaluating whether these frameworks manage to identify clearly and exhaustively the multiple dimensions that need to be addressed to generate improvement in the area, and whether they succeed in providing strategies to implement these improvements in practice.

Current mining sustainability frameworks tend to be deficient in three main areas: firstly, on understanding sustainability as a coherent and integrated concept and not a list of separate issues; secondly, on understanding the specificity of mining compared to other sectors, which is that it extracts on non-renewable resource out of the ground; and thirdly by underestimating the repercussions of the lack of economic viability.

The connection between economic instability and a lack of efficiency in the extraction of the mineral resource at the mine site level was highlighted. This suggests that current mining sustainability frameworks could potentially gain by placing the management of the local mineral resource at their core, and use it as a central dimension from which other sustainability dimensions can be integrated from.

The following section presents the industrial ecology field of research with its main definitions and methods, reviews current applications to mining systems and discusses how industrial ecology can be used to identify improvements in the mining industry's contribution to sustainable development.

2.2. Industrial ecology

This second part examines the potential of the industrial ecology field to deliver a mining sustainability framework that encompasses the sustainability dimensions most relevant to mining and assesses the sustainability performance of a mine site in a systematic way. First, an overview of the industrial ecology field is provided, its main definitions, what principles it builds on and what practical analytical tools have emerged from industrial ecology thinking. This part ends with a particular attention on how these tools have been or could potentially be used in the mining context.

2.2.1. Short history of the field

Industrial Ecology (IE) is a relatively recent discipline. It was named for the first time in a 1989 article written by Robert Frosch and Nicholas Gallopoulos in the Scientific American and titled "Strategies for Manufacturing" (Frosch & Gallopoulos 1989). Three years later a National Academy of Science Colloquium was organised around the theme of industrial ecology. Scholars from various research fields were brought together and produced a number of papers defining the key features and research objectives of this new discipline (Ausubel 1992).

Fifteen years later Harper and Graedel (2004) reviewed the "teenager's progress", evaluating the evolution of Industrial Ecology as a research field. In 2004, after the theoretical work of conceptualizing industrial systems through the development of analytical tools such as Life Cycle Assessment and Material Flow Analysis, the IE field started to gather data to characterize these systems. The knowledge acquired from this work has now to be used to address the need for a sustainable global economy. According to Harper and Graedel, IE's research results offer the means to stimulate the development of sustainable industrial ecosystems.

Several authors have called industrial ecology the science of sustainable development (Allenby 1999; Ehrenfeld 2000; EMF 2015; Lifset & Graedel 2002) though others have argued that some aspects of sustainable development have not been tackled appropriately (e.g. Korhonen 2004; van Berkel 2007), underlining a research gap in the social dimension of sustainable development. However, Korhonen (2004) insists that IE is well equipped to fill this gap in the future. Beyond the ongoing debate, IE researchers agree on the great potential of this new field. Harper and Graedel (2004) estimated that industrial ecology is "the closest approximation to a more systematic and quantitative approach to sustainability". Similarly, Erkman (1997) stated that IE can provide concrete answers to the question: "How can the concept of sustainable development be made operational in an economically feasible way?"

Now the field has entered adulthood and its influence on other disciplines and in decision-making processes has become more significant (CIE 2014a). Industrial Ecology based analytical tools are used in the Intergovernmental Panel on Climate Change's (IPCC) 5th Assessment Report to quantify the contribution to climate change of major industrial sectors (IPCC 2013). IE specialists have recently published in Science, Nature and the Proceedings of the National Academy of Sciences and authored some of UNEP's International Resource Panel Reports (CIE 2014a). Finally, industrial ecology and the closely related concept of circular economy are now being used in political decision-making in the European Union as well as in Japan and China (CIE 2014a).

2.2.2. Industrial ecology definitions

There are in fact numerous definitions of industrial ecology each bringing additional and complementary perspectives while still being consistent with the overall concept of IE. The following section gathers and comments four of them.

2.2.2.1. Circular flows and interface with the environment

The early days of industrial ecology constituted in a theoretical reflexion on the conceptualisation of industrial systems. This reflexion revolved around Frosch and Gallopoulos' (1989) initial definition of industrial ecology, called the "biological metaphor", which made the comparison between natural ecosystems and man-made systems. The idea was that natural ecosystems could serve as potential models for innovation for man-made systems as they are examples of long-lived, robust and resilient systems (Ehrenfeld 2000). Reuter et al. (2005) later reformulated this first definition of industrial ecology (see Table 2.4).

Table 2.4: Industrial ecology definitions

Reuter et al. (2005)	industrial ecology is "a concept of engineering and management adapting typical ecosystem features: feedback (control) loops, minimal use of resources and minimal production of wastes by cascading the use of resources and energy"
Robert White (White, R 1994)	industrial ecology is "the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources. The objective of industrial ecology is to understand better how we can integrate environmental concerns into our economic activities"
Yale Centre for Industrial Ecology (ResearchMedia & CIE 2013)	"industrial ecology (IE) is a multidisciplinary field that analyses material, water, and energy flows of industrial and consumer systems at a variety of spatial scales, drawing on environmental and social science, engineering, business and policy."
Graedel, T and Allenby (1995)	"The means by which humanity can deliberately and rationally approach a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surroundings, but in concert with them. It is a system view in which one seeks to optimize the total material cycle from virgin material, to finished material, to components, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy and capital"

Man-made systems started as linear systems, consuming resource and generating waste. The authors of the biological metaphor argue that, in order to be sustainable in the long term and they should eventually adopt a fully cyclical metabolism, that is to say close the material cycles by turning the waste of one process into the resource of another. In order to do that, 'detritivores' and 'scavengers' in human systems are needed in order to close the loop (Ehrenfeld 2000). Furthermore, industrial systems - and human society as a whole - need to be integrated into their environment (Brattebø et al. 2007). As a result IE not only investigates the flows within our society but also between our society and the environment, examining our natural resource use and the sinks where waste is deposited.

This first definition is, according to Harper and Graedel (2004), at the core of the IE field and the “ecology” word in “industrial ecology” directly derives from this concept that has shaped IE thinking since then. The “industrial” word relates to the view that firms are the system’s components that need to be reorganised through innovation, with a deep restructuring in the way they interact with each other as well as in their own internal metabolism.

2.2.2.2. Multi-disciplinary and systemic thinking

Another significant definition of industrial ecology was formulated by Robert White in 1994 (see Table 2.4), and provides a more practical perspective. It builds on the basis of the biological metaphor to deduce the scope of the field: what is being studied and how. Two other definitions gathered in Table 2.4 are those of Graedel, T and Allenby (1995), and, more recent, the Centre for Industrial Ecology at Yale University (ResearchMedia & CIE 2013). These three definitions aim at defining industrial ecology as a field of research.

Sustainable development, which is the main target of the IE field, necessarily involves a deep restructuring of all human activities. Hence, it has to be addressed at multiple scales (CIE 2014a): unit processes, products, supply chains, facilities, industrial parks, firms, cities, regions, and the entire globe. This integration can only be done through collaboration between disciplines. Industrial systems remain the subjects of the study; nevertheless, it is clear that monetary flows are closely linked to material and energy flows and decisions made in the political, legislative and social spheres will influence industrial systems and hence need to be considered.

Taking a systems perspective is fundamental in the IE approach as it avoids problem displacement from one part of the system to another. A first step in all IE analyses is to define the boundaries of the system under study and thus make sure to encompass all relevant elements.

The three IE definitions call for the need to design quantitative tools to measure a system's sustainability performance. Industrial Ecology aims at becoming a well-established systems science (ResearchMedia & CIE 2013) able to inform decision-makers.

2.2.3. Industrial ecology methods

Eventually, what characterizes the IE field is that it is a "cluster of concepts and tools" (CIE 2014a). It can however be challenging to position Industrial Ecology and related IE tools in the large constellation of environmental and sustainability frameworks - as shown by the review articles of McLellan et al. (2009) and Glavič and Lukman (2007). Brattebø et al. (2007) presented some of the most important Industrial Ecology tools and methods. This section presents those that have been applied to the mining industry and reported in the academic literature. The quantitative character of these tools as well as their large system scope have a potential to inform decision-making. They all have their own advantages and limitations and are more or less suited to a particular system of study as they provide different viewpoints and use different metrics. In some cases, these tools may also be adapted or/and used in combination to address a particular situation.

2.2.3.1. Life Cycle Assessment

Life Cycle Assessment is one of the oldest and most used IE tools and its inclusion in the environmental management standards ISO 14000 has made it a reliable framework (ISO 14040:2006). In Life Cycle Assessment (LCA) the system under study is the life cycle of a product or an activity. Product LCAs analyse the environmental impacts of a product from raw material extraction to its final disposal as waste, in simple terms from cradle to grave. LCAs are comparative studies, and compare different options that all deliver a common function called functional unit. For example, an LCA can compare the environmental performance of two personal cars both driving one thousand kilometres. Another example would be the comparison between three one-litre glass bottles: one made of virgin glass, one made of recycled glass and one that has been washed and reused. LCAs require a careful definition of the functional unit as well as the system boundaries, especially in cases such as recycling where the cradle-to-grave line is closed.

Life Cycle Assessment, as one of the most mature IE tools, presents a high potential to assist the mining industry in identifying areas of improvement (Norgate & Haque 2010).

When the International Council on Mining and Metals (ICMM) joined the Life Cycle Initiative, founded by UNEP-SETAC in 2002, the ICMM positioned itself as a promoter of life cycle approaches (Yellishetty, M. et al. 2009).

However, LCA applications to mining are still limited. Norgate and Haque (2010) consider that most product-LCAs do not include the mining stages in enough details and this is because of the lack of publicly available data. Awuah-Offei and Adekpedjou (2011) argue that it is the lack of life-cycle thinking in the mining industry that is preventing the development of this tool.

There is, however, a few LCAs focused on the mining and mineral processing stages. While product-LCAs follow the cradle-to-grave concept (or cradle-to-cradle in the case of recycling), an LCA focused on these upstream stages would define its system boundaries as 'cradle-to-gate'.

Among these LCAs, Durucan, Korre and Munoz-Melendez (2006) proposed a model called LICYMIN designed for minerals production LCAs. The main objective of this model was to represent the mining system in a comprehensive way. In particular, the model considered the case of mines that produce several mineral concentrates. Stewart and Petrie (2006) also produced a synthesis of minerals production processes through the use of Life Cycle Inventories (LCIs; these are the data-gathering stage of LCAs). The study led to the creation of flow sheets encompassing all mineral processing activities and usable for cradle-to-gate LCAs. However, it excluded the extraction stage. Blengini et al. (2012) provided an interesting LCA framework applicable to all mining systems combining three interdependent life cycles: project, asset and product. This approach allows accounting for the transient nature of mining projects that, unlike other industries, operate only for a limited period of time. The entire life cycle of a mine project, from planning to closure and rehabilitation is therefore relevant to consider.

Memary et al. (2012) present a time-series LCA approach to examine the historical environmental impacts associated with copper mining and smelting in Australia from 1940 to 2008. The analysis gathered data on five mines that represent 60% of national production and present diversity in both geography and technologies. Data was gathered and compiled from the National Pollutant Inventory, the National Greenhouse Accounts Factors and the Australian LCA inventory released by Life Cycle Strategies Pty Ltd.

Suppen et al. (2006) present a more classical Life Cycle Inventory for the production of base metals in Mexico in 2000, using publicly-available data. The functional unit is one tonne of concentrated mineral. Norgate and Haque (2010) also used public data and defined the functional unit as one tonne of ore or one tonne of concentrate ready for ship loading. Mine site rehabilitation was not included in the study and all mine sites considered produced a single product.

Recent research presented by Pell, Wall and Yan (2016) focuses on rare earth elements and compares two mine sites with similar mineralogy with respect to their energy consumption and greenhouse gas generation. In this analysis, the functional unit is defined as one kilogram of a rare earth oxides mix. The results show that energy requirements are significantly lower when the milling stage is skipped in one of the two mines. However, skipping the milling stage would have resulted in an overall lower resource recovery.

Other LCAs were performed with system boundaries more restrictive than the cradle-to-gate approach. Norgate and Lovel (2004) performed an LCA focusing on water consumption. Norgate and Jahanshahi (2010) took a life cycle perspective in order to compare the technologies' performance in processing low-grade ore. Awuah-Offei, Checkel and Askari-Nasab (2009) compared a belt conveyor and truck haulage systems to transport the ore from an open pit mine. Adachi and Mogi (2007) developed a mining life cycle inventory database focussing mainly on greenhouse gas emissions and applied it to copper and zinc metal production in Japan.

A few mining LCAs investigated more closely the waste aspect of mining. Reid et al. (2009) performed an LCA of tailings management options. Hengen et al. (2014) compared active and passive treatment options for acid mine drainage (AMD) wastewater. Tuazon and Corder (2008) compared two options for the treatment of acid mine drainage (see 3.2.1 for a definition of AMD), one involving the re-use of bauxite residue and the other one using lime. These studies are useful in providing quantitative information for the complex decisions involved in mine waste management. One of the important trade-offs to consider is identified by Reid et al., and is the generation of external impacts (due to higher resource and energy use) in the aim of remediating of local impacts.

However, the system boundaries chosen are too narrow to allow integrating waste management within the mine's overall environmental footprint. On the other hand, Durucan, Korre and Munoz-Melendez (2006) consider that cradle-to-gate LCAs have been overly simplified and do not emphasise enough the waste management stage.

LCA practitioners have reported some of the difficulties they encountered in applying LCAs to mining, notably:

- Mines that produce several outputs: this leads to difficulties to allocate environmental impacts to one particular metal and define an appropriate functional unit for the analysis (Awuah-Offei & Adekpedjou 2011). This issue is addressed in Durucan, Korre and Munoz-Melendez (2006)'s framework.
- The unique character of every mine site: according to Blengini et al. (2012) and Basu and van Zyl (2006) LCA frameworks are well designed to be applied to standardised production systems, and mine sites are typical examples of non-standardised production systems. Each ore deposit has unique characteristics to which mine projects have to respond appropriately.
- Some LCA practitioners conclude that a special set of environmental impacts should be defined for mining LCAs (Blengini et al. 2012). Reid et al. (2009) insist on the importance of land use and land transformation as an indicator. Hansen (2004) develops an impacted land indicator and dedicates her doctoral thesis to the understanding of the pollution generated by mining waste. Schneider et al. (2014) propose a new environmental impact for mining LCAs called the "economic resource scarcity potential", which would be an accurate indicator to measure resource depletion (see 2.3.3.1 about the importance of resource depletion).
- The lack of publicly available data, especially on waste and mining legacies (Norgate & Haque 2010).

These significant limitations need to be addressed in order to perform reliable LCAs in the mining industry. Additionally, and with respect to what was discussed earlier, the need for an improved resource recovery at the mine site level should be taken into account in the definition and selection of an LCA's functional unit, system boundaries, impact categories and data inventories.

2.2.3.2. Material Flow Analysis, energy and exergy

- Material Flow Analysis

A Material Flow Analysis or Material Flow Accounting (MFA) draws a comprehensive picture of the flows and stocks of one material within a particular system, typically a region, an industrial sector or an industrial area. The scale of the system can vary greatly as some MFAs are performed at a global level (CIE 2014b). The focus is on technical processes, accounting for their inputs, outputs and inner stocks. The numbers are usually aggregated for one year, but the analysis can be made dynamic by extending it over several years. MFAs can be done in a bulk accounting way or in a specific substance tracking way, i.e. selecting one element contained in different materials (e.g. iron). This more common type called Substance Flow Analysis allows encompassing the flows of the given substance in the environment or its accumulation in waste deposits.

Global material flows have been studied in the Substance Flow Analysis literature but with no particular focus on mining, except for some rare studies, such as Gordon (2002) and Yellishetty, M. and Mudd (2014). Another significant Substance Flow Analysis study that includes mining-related flows is the one from Hatayama, Tahara and Daigo (2014), who investigate the potential for metal gleaning, comparing the benefits of increasing metal recovery rates at the mine site level with the ones of recycling end-of life products. The indicator used for this analysis is the change in the resource’s depletion time. The results show that for many base metals (iron, aluminium, zinc, copper, nickel and silver) improving mineral processing recovery rates would prove to be more efficient than improving recovery from post-consumer waste. This study does not include mining processes situated upstream of the mineral processing stage, which also generate waste (Lottermoser 2010). If these additional waste streams were to be included in future mining Substance Flow Analyses, they would provide an additional argument in favour of investigating mineral losses at the mine site level. Gordon’s study leads to similar conclusions and is presented in more details in 3.1.2.

No example of bulk MFA applied to mining activity was found. However, Eurostat, the statistical office of the European Union, developed a methodology using indicators for economy-wide material flow accounts (Eurostat 2001) - i.e. bulk MFA. These indicators have been adapted by Sendra, Gabarrell and Vicent (2007) to be applicable to smaller region such as industrial areas. Such translation could also potentially be done for a mining site. The mining industry could potentially benefit from MFAs or SFAs that map flows and stocks of material within a mine site, in particular to localize remaining metal in mine waste.

- Energy and exergy

Energy flows are closely intertwined with material flows through the notion of embedded energy. LCAs can also include an energy use category in its environmental impact accounting. Energy analysis is typically used to identify the possibilities for energy conservation in a given region (Brattebø et al. 2007). Exergy analyses allow measuring internal transformations of matter and energy in resource extraction and consumption (Nguyen, Ziemski & Vink 2014). In particular, exergy allows identifying areas of potential technological improvements since exergy losses directly relate to process inefficiencies. According to Gößling-Reisemann (2008b) other IE tools, such as LCA and MFA focus on quantifying the flows and their impact on the environment, but not on the flows' quality within the technosphere, which exergy analyses can do. If the flow's quality is improved this would automatically result in a decrease in inputs from and outputs to the environment. Bösch et al. (2007) investigated the possibility to include an exergy indicator in the LCA methodology.

Exergy analysis is a tool relevant to the mining industry and for considerations on sustainable resource management. Ayres, Ayres and Masini (2006) argue that exergy is the most suitable indicator for accounting resource use and waste generation. In particular, the exergy content of a waste residual can be viewed as its potential for doing harm to the environment, as reactive materials will have high exergy content. However, exergy analyses have not commonly been used for this role.

Ayres, Ayres and Masini (2006) performed an exergy analysis and compared the performance of the steel, aluminium, copper, lead and zinc industries in the US. Valero, Valero and Arauzo (2008) used exergy-based indicators to assess the degradation of mineral deposits over history. Gößling-Reisemann (2008a) performed an entropy analysis on copper production. Nguyen, Ziemski and Vink (2014) applied the exergy approach on a mine water system in order to understand its energy demand and identify key areas where water use efficiency could be improved.

2.2.3.3. Eco-efficiency, resource efficiency, and other indicators

Eco-efficiency (EE) is an indicator regularly used by companies who look for eco-efficient solutions that maximize the value added of their operations while minimizing the environmental impacts. The definition of what constitutes the eco-efficiency indicator is left to the user depending on his/her need. Generally, eco-efficiency is a ratio of economic and environmental performances, its most common type being economy-over-environmental-impact, also called environmental productivity (Brattebø et al. 2007).

In the mining industry, productivity indicators, notably labour productivity and capital productivity, are regularly calculated, and aim at measuring technical progress as well as the efficiency of production (ABS 2016). The Australian Bureau of Statistics recently included the mineral resource in its productivity calculations (ABS 2016). However, only the mineral fraction that is produced and sold is taken into account. If the efficiency dimension proposed by Laurence et al. (2011) were to be taken into account, mineral production would be weighed against the entire mineral deposit, including the minerals that are not recovered. Developing a methodology for the calculation of environmental productivity in the mining industry would allow to incorporate environmental considerations in an already existing performance framework.

Mitchell et al. (2014) underline that initiatives to improve productivity in the mining industry have mostly been focused on cost cutting and valuing volume over efficiency. According to Mitchell et al. (2014) this leads to modest and short-term results, which have been unsuccessful, as the Australian mining industry has been registering poor productivity performances for the past decade. More integrative and systemic approaches would ensure each part of the business is optimised and increase the overall performance, and Mitchell et al. underline that addressing this integration gap is important.

Van Berkel (2007a) defined five resource productivity themes relevant to the mineral industry: effective resource utilization; reduction of process waste and enhancement of co-product values; reduction of water use and impacts; reduction of energy consumption and greenhouse gas emissions; improvement of control of toxic material. Similarly, recent research from Spuerk, Drobe and Lottermoser (2016) define and test a resource efficiency indicator for the mining industry. This indicator is an aggregate of four main resource indicators: water, energy, land and mineral deposits.

Finally, Rönnlund et al. (2016a) developed an eco-efficiency indicator framework for the mining industry, highlighting that resource depletion and resource efficiency are key issues to be addressed. The framework involves 10 groups of indicators and 32 indicators in total aiming to assess the environmental sustainability of the mining industry's products. This indicator set is meant to be comprehensive and include all environmental impacts relevant to mining, including the efficiency of all resource use (e.g. water, energy, land, chemicals) and the efficiency of mineral extraction. In a second paper (Rönnlund et al. 2016b), data are then gathered to establish a benchmark for each indicator, in the aim of allowing comparison and evaluation a mine site's performance. However, most of the indicators relating to extraction efficiency were either not benchmarked or benchmarking was deemed unreliable, due to lack of data.

Overall, using an indicator framework in the context of this thesis would provide flexibility to evaluate the performance of a mine site related to the efficiency of mining operations. Developing new indicators could allow relating and comparing them to productivity indicators that are currently used by the industry and policy makers, and thus identify opportunities for improvement of these existing indicators.

2.2.3.4. Eco-design, industrial symbiosis and procedural methods

The methods and indicators presented above can support decision-making via a modelling quantitative system analysis. Much less addressed in the literature, eco-design and industrial symbiosis on the other hand are procedural methods that focus on the restructuring of organisational, management and legal spheres (Brattebø et al. 2007). Procedural methods are to be applied after the analytical methods, and can be found at the governmental level and policy instruments can encourage directly the implementation of solutions identified by industrial ecology modelling. The Extended Producer Responsibility and the Integrated Product Policyare examples of such methods (Brattebø et al. 2007).

Eco-design focuses on the design phase of a product, adopting life cycle considerations to design a product in a way that is environmentally beneficial. Many examples of eco-design can be cited and aims can vary: design for recycling, design for disassembly, which would facilitate both recycling and repair, design for the environment that focuses on the overall product's impact etc. Eco-design, often called sustainable product design, is primarily if not solely used in the manufacturing industry. It could however be potentially adapted to the mining industry, as mines' products, the mineral concentrates, hold physical, chemical and mineralogical properties that can to some extent be 'designed'. The "Designer Tailings" project (Edraki et al. 2014) on the other hand, regards tailings as a material whose biogeochemical properties could potentially be designed, through modifications in the upstream processes, thus improving the integration of tailings management in mine planning.

Finally, the concept of industrial symbiosis, or regional resource synergies, a practical application of industrial ecology at the regional scale, has also rarely been used in a mining context, primarily because industrial symbiosis is considered to rely on geographical proximity and mine sites are generally located in remote areas. The only industrial symbiosis analysis focused on mining activities found in the literature is the study from Salmi (2007) who investigated a hypothetical case of industrial symbiosis in the Kola Peninsula mining region in Russia. Other industrial symbiosis studies in metal production mostly focus on metallurgical processing industries thereby excluding the upstream mining stage (Golev 2012; van Beers et al. 2007).

Salmi (2007) defined industrial symbiosis as the increased number of connections between businesses and relates it to an improvement in eco-efficiency. This study shows that industrial symbiosis leads to an increase in resource recovery. In this study, the author investigates a production model called 'complex utilization', similar to industrial symbiosis and designed by the Soviet Union for a mining region in the Kola Peninsula in Russia. Salmi compares the hypothetical development that this production model would have led to with the actual post-Soviet development of the mining region. The study shows that industrial symbiosis would have resulted in an increased eco-efficiency and an increased production, but not in a decrease in the overall environmental burden.

The author concludes that the traditional end-of-pipe technologies that were implemented in the Kola Peninsula may be more desirable than industrial symbiosis, because they led to a reduced environmental burden. This conclusion however overlooks the fact that the actual development of the mining region resulted in a significantly lower production than the complex utilization model. The avoided environmental impacts are due to an avoided production; the actual development of the mining region led to both an increase in environmental burden per unit of output (i.e. a decreased eco-efficiency) and a decrease in the output per total natural resource available (i.e. a decreased resource recovery). Industrial symbiosis would have therefore lead to higher resource recovery and hence made the mining operations more sustainable in that respect.

2.3. Conclusion: defining the boundaries of the research project

2.3.1. Gap in the literature: reconciling the industrial ecology field with the mining industry

The underlying principles of the biological metaphor are considered by industrial ecologists to be a basis for a sustainable restructuring of our society. Cyclical flows promoted by the metaphor result in decreasing linear flows, that is to say raw material extraction and final waste disposal. Ayres (1997, p. 14), one of the industrial ecology pioneers, confirms “an ecologically sustainable economic development […] will require comparably massive reductions in primary metal [consumption]”. This may explain why IE applications to mining are currently limited, while many industrial ecology studies investigate the benefits of recycling metals downstream of the value chain, attempting to close the loop in the manufacture and consumption stages.

However, the purpose of the industrial ecology field is to study all industrial and consumer activities, and assess them in terms of their inner metabolism, their impact on the environment and their place and value in a more sustainable society. Mining is an integral part of global metal cycles studied in industrial ecology, and is a relevant stage to include in the mapping of stocks and flows that occur because of human activities. The mining industry is critical in the pursuit of sustainable development as it stands at the interface between human society and its natural environment, extracting the resources that feed all the other sectors and generating extensive amounts of waste and pollution in return.

The industrial ecology definitions presented above show that industrial ecology may be well suited to evaluate how the mining industry can adopt practices that are more consistent with the principles of sustainable development. Achieving sustainable development is the field’s main objective, although it has certain shortcomings in encompassing the social pillar. To achieve this objective, the field provides a variety of tools designed to perform quantitative analyses at a system level, and applicable to a wide variety of systems and scales. Section 2.1 identified that most mining sustainability frameworks were limited in integrating the various dimensions or principles of sustainability, as well as implementing them in practice, which requires the ability to measure the system's performance. Applying an industrial ecology framework comprised of well-chosen modelling tools to a mining system could potentially ensure that overall-system improvements are identified and synergies and trade-offs are appropriately considered. However, significant developments in the industrial ecology field still need to be made for such an all-inclusive framework to be built. Currently, IE is a good approach for research in mining to make progress while aligning with sustainable development objectives. This is particularly true in the areas of local environment preservation (which would induce concomitant benefits to local communities), and the eco-efficient use of mineral resources.

Section 2.1.2 also identified two areas that are undervalued in the main existing mining sustainability frameworks - the ICMM's ten principles, the Seven Questions to Sustainability, and the Five Capitals framework: firstly, the need for an optimum extraction of the - non-renewable - local mineral resource in a way that minimises losses, and secondly, the repercussions of the lack of economic viability on these losses. An IE analysis focusing on mineral flows at the mine site level could provide useful insights on these key aspects.

2.3.2. Defining the system under study

Applying industrial ecology methods to the mining industry first requires defining the system to be studied. Section 2.1 highlighted the importance of optimising mineral resource extraction at the mine site level, and the several drawbacks of leaving mineral resource behind. In order to understand better this specificity of the mining industry in its contribution to sustainable development, it is therefore relevant to pay closer attention to flows and stocks of mineral resources within a mine site. An appropriate system boundary for such study would be, on the spatial level, the mining lease, and an appropriate time horizon would be the mine's life cycle, from ore discovery to final relinquishment of the lease. This time horizon is important as it allows observing the effect of premature closures or, alternatively, prolonging mining activities. Following Robert White's definition of industrial ecology (1994), the study of a mine site's metabolism would then focus on understanding the flows of mineralised material, their impact on the environment, and the influence of economic, political, regulatory, and social factors on these flows.

In particular, it is relevant to pay closer attention to the sources of inefficiencies in the extractive process, and be able to quantify the mineral losses that occur as a result. At the mine site level, waste flows have received little attention from industrial ecology studies, and the resulting dissipation of mineral resources, as well as in their impacts on the environment, are still poorly understood.

The preservation of non-renewable mineral resources is a well addressed topic in the industrial ecology field, and numerous studies quantify notably the in-use stocks of metals within our society, in order to assess the benefits of metal recycling (e.g. Haas et al. 2015). This thesis argues that mining waste present in both closed and currently operating mines should be included in these in-use stocks. Similar to scrap metal from manufacturing industries, mining waste is an industrial reject that industrial ecology can help minimise and create value from. The role of mine waste management as a key subsystem that stands at the intersection between the environmental and the economic spheres is the subject of chapter 3.

2.3.3. Building the methodology

Applications of specific industrial ecology tools to mining appear to be still limited and suffer from methodological issues that need to be addressed. However, the review of industrial ecology tools applied to mining allowed drawing some intermediate conclusions that will help building an industrial ecology framework applicable to mining operations:

- The literature review has found that Life Cycle Assessment was currently the most commonly used IE tool, as well as the most commonly applied to mining. However, LCAs are data intensive, and would therefore require an active participation of the mine operator to provide data on the consumption of energy, water, chemicals etc. Besides, significant methodological issues still need to be addressed before a cradle-to-gate LCA can provide reliable results. In particular, more relevant environmental impact categories need to be developed; the unique characteristics of each ore deposit lead to issue in the tool's standardisation; and the mineral resource needs to be more carefully encompassed in the system boundaries and in the definition of the functional unit.
- Exergy and Material Flow Analyses, though significantly less prevalent in the mining literature, present an adaptability that is attractive in the context of this research.

Besides, the variable data requirements in bulk MFAs can be suitable when the transparency of case study mining companies is limited. The MFA methodology is characterised by geographical system boundaries, which would allow taking a mine site as system and observing its internal flows and stocks of material. Substance Flow Analyses also allow to choose particularly relevant substances (e.g. a certain set of minerals) and focus on their flows.

- Indicators such as eco-efficiency and resource efficiency could potentially be integrated to existing performance frameworks for the mining industry. They offer flexibility as well as the possibility to place some emphasis on the efficiency of extraction. A comprehensive indicator framework designed for the mining industry is the one developed by Rönnlund et al. (2016a), which suggest industrial ecology indicators are appropriate to assess a mine's contribution to sustainable development, provided sufficient data are available.
- While analytical tools presented above are useful to provide a quantitative assessment, industrial ecology procedural methods focus on the organisational implementation of the results. Applications to mining are rare, and this lack of support from the literature makes it challenging to address this aspect in this thesis. However, this aspect of the industrial ecology methodology defined by Brattebø et al. (2007) shows that, after the essential analytical stage, it is important to discuss the practical implementation of the results and consider how the different actors can organise and influence a desirable change in practice. While the analytical stage allows for the understanding of the system under study, as well as quantifying key aspects of its internal metabolism, and identifying critical issues, a procedural stage can help strategize future actions and identify pathways for change.

Overall, the review of industrial ecology tool applications in the mining industry shows that there is scope for significantly building on and further incorporating the foundations of industrial ecology into mining projects. The thesis therefore aims at reinforcing these foundations and strengthening the link between industrial ecology and mining activities rather than focussing on more specific methodological issues.

3. The Mine Waste Management hierarchy

In this chapter, mine waste management is examined from an industrial ecology perspective, i.e. by relating mining waste to the industrial system that generates it, and seeking opportunities to recover or prevent mineral losses through waste minimisation. Section 3.1 defines mining waste and provides estimations of amounts and mineral content. Section 3.2 describes the main environmental impacts related to mining waste, their significance in the mine's entire footprint, as well as the contribution of unrecovered minerals to these impacts. Section 3.3 on the other hand introduces an alternative way of considering mining waste, by identifying opportunities that could create value, and how this would translate in a fundamentally different mine waste management. In section 3.4, a hierarchy of practices is developed with the aim of setting preliminary guidelines for a desirable change in mine waste management. This hierarchy is illustrated with examples of existing practices as well as current research work.

This chapter was the subject of two publications in the journal of Minerals Engineering (Lèbre, Corder & Golev 2016), and in Resources (Lèbre & Corder 2015), and significant parts were extracted from these papers to write this chapter.

3.1. Mine waste classification and global trends of waste generation

In this section, the processes that generate mine waste are reviewed and factors influencing waste amounts and composition are explored. This is then illustrated with estimates of global mine waste generation for major base metals.

3.1.1. What is mine waste and how is it generated?

Figure 3.1 provides a simplified representation of the main processes involved in mining and which waste streams they are responsible for. It should be noted that this simplification is mainly suitable for precious and base metals (i.e. the hard rock industry), and does not include more specific processes such as those involved in aluminium production. Mine waste generation through processing is more complex than what is shown in Figure 3.1, and the mining industry produces a large range of minerals as well as different kinds of mineralised and non-mineralised waste material. Figure 3.1 is focused on the main streams of mineralised waste.

There are three main processes in metal mining that generate waste: mining itself, which is the extraction of the ore from the ground; mineral processing, which produces a mineral concentrate out of the ore; and metallurgical processing which generates a refined metal out of the mineral concentrate (see Figure 3.1).

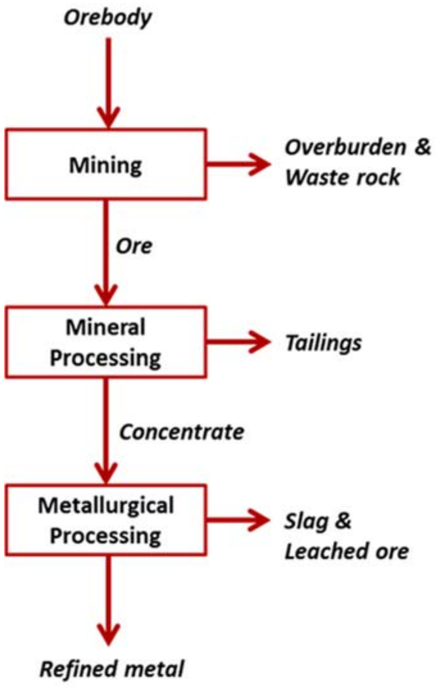

Figure 3.1: Schematic product and waste streams at a metal mine

Mining is the first stage of the exploitation of a mineral resource. Lottermoser (2010) simply defines it as "the extraction of material from the ground in order to recover one or more component parts of the mined material".

Mineral processing, also called beneficiation or concentration, is the separation of the valuable minerals contained in the ore from the gangue, which is the name given to the worthless material surrounding the minerals in the ore. This includes processes such as: crushing, grinding, flotation and gravity, magnetic or electrostatic separation (Wills & Napier-Munn 2006).

Metallurgical processing is generally done in two different ways: hydrometallurgy and pyro-metallurgy, although electrometallurgy is another less common option (Lottermoser 2010). Hydrometallurgy (or leaching) relies on the use of solvents (e.g. cyanide or sulphuric acid) to dissolve the wanted metals while pyro-metallurgy (or smelting) uses heat to break down the crystalline structure of the ore mineral. In both cases, the chemical combination of the minerals is broken to release the metal in its pure form.

While hydrometallurgical processes typically occur on the mine site, electro and pyro-metallurgical processes are mainly situated off-site (Lottermoser 2010). The reason is that electro and pyro-metallurgical processes are energy intensive and mine sites are typically located in remote areas where energy is expensive. However, there are other factors that determine where a metallurgical processing operation will be held. For example, pyro-metallurgical processing generates sulphuric acid as a by-product while hydro-metallurgical processing is a net consumer of it. This can constitute an incentive for these two operations to be combined (Ayres, Ayres & Råde 2002).

It is also worth noting that in some cases of very high grades the ore can be directly sent to the smelting stage without previous mineral processing, or with a very basic processing stage. This is sometimes the case for iron ore for example that can contain on average 60% of iron (Wang, Muller & Graedel 2007).

Therefore, depending on the site, a mining company may perform only the mining stage, or it may include a mineral processing stage as well, and sometimes it can have a smelter. In the majority of cases however, a mine site performs the mining and mineral processing operations (Lottermoser 2010).

Three main types of waste are generated by these three activities (see Figure 3.1):

- Overburden and waste rock

It is the material that covers or surrounds the ore body and that has to be removed in order to access the economical material. Generally, overburden is considered to have no mineral part whereas waste rock may have some in low quantities. What distinguishes waste rock from ore, that is to say, what is economical to extract and what is not, is the cut-off grade: under a certain mineral percentage, the material will be treated as waste. The value of the cut-off grade will depend on all the factors that determine the costs of the overall mining operations. For example, surface mining (in an open pit) is typically much cheaper than underground operations; as a result, open cut mining can afford to have a much lower cut-off grade. Mineral extraction is scheduled and the cut-off grade is updated year after year to adapt to change in costs and in metal prices in order to ensure an economically viable operation.

- Tailings

Mineral processing of the ore generates tailings. Because of milling and flotation, they are generally finely grained rocks in suspension in water. The ore grade will determine how much tailings are produced. For example, the mineral processing of 100 tonnes of copper ore with a 2% grade will roughly generate 98 tonnes of dry tailings, to which must be added the water content. The grade varies greatly from one metal to another.

Beneficiation processes are not 100% efficient in performing the separation between minerals and gangue: the mineral concentrate produced still contains a significant percentage of gangue and valuable minerals also end up in the waste stream. The mineral recovery rates will be highly dependent on the technology chosen and how adapted it is to the specificity of the ore (e.g. its mineralogy). The recovery rates also depend on the required concentrate grade: the higher the grade in the concentrate, the lower the recovery rate (Wills & Napier-Munn 2006). The concentrate grade will be determined by the contract between the mine and the downstream metallurgical processing.

- Slag and leached ore

Slag is the solid waste produced by pyro-metallurgical processing. While pyro-metallurgy is less common on mine sites, slag deposits may remain from historical operations. Hydro-metallurgical processing generates another significant waste deposit in mine sites: leached ore. After being crushed in the mill, the ore is deposited as a heap leach pad and acid runs through it to extract the wanted metal. When the remaining ore’s grade is considered uneconomical the operations end and the leached ore is left as waste.

Waste rock, tailings, slag and leached ore represent the largest deposits on a mine site. However, there are several other types of mining waste. They include atmospheric emissions, flue dust, wastewater, disused equipment and infrastructure etc. In particular, water is a key element in mine sites and is used in nearly all mining processes (Lottermoser 2010). When introduced during one of the production stages, water comes in contact with mineralised material and becomes charged with dissolved metals. Some of them as well as other contaminants remain in the wastewater after it has been used. In addition to process water, natural water flows, surface or underground, also come in contact with mineralised material by infiltrating mining waste deposits and also contribute to unwanted movements of minerals and contaminants.

3.1.2. Mine waste volumes and composition

Lottermoser (2010) estimated that the global mine waste deposit was in the order of several hundred billion tonnes, covering an area of a hundred million hectares, which would be the same order of magnitude as the materials moved by the natural geological processes that have shaped our planet. In particular, metal mine waste generation would be currently averaging 15 billion tonnes per year. This is ten times larger than global municipal waste generation, which was estimated to be 1.3 billion tonnes in 2012 (Worldwatch Institute 2012).

Over the past decades, mine waste generation has been increasing significantly and this trend is likely to continue in the future (Hudson-Edwards, Jamieson & Lottermoser 2011), though Bringezu (2014) pointed out that it could be partially offset by other factors such as the growing trend for underground mining. Indeed, underground mining generates less waste rock than open cut operations as it primarily only transports ore up to the surface.

Mining is by far the industry that generates the most waste (Lottermoser 2010). Coal mining is the first in line, followed then by metal mining industries. Extraction and production of clay, sand, gravel and other industrial minerals generally produce much less waste.

From one metal to another, waste generation can vary markedly. This depends mostly on the ore grade that is directly related to the amount of tailings produced. Lottermoser (2010) stated that for every tonne of metal ore extracted, at least a tonne of solid waste is generated, but often the amounts of waste are orders of magnitude greater. Table 3.1 presents mine waste generation data for common metals in Australia and shows that the tailings-production ratio varies from 0.25 for iron to 800,000 for gold, and these figures do not take into account waste rock.

Table 3.1: Metal mine waste generation in Australia for the year 2012 in kilotonnes (Mudd 2014)

	Production**	**Tailings**	**Waste rock**	**Tailings/ Production ratio**
Iron ore (concentrate)	520,000	130,000	no data	0.25
Bauxite (concentrate)	76,280	19,000	no data	0.25
Copper	914	132,000	>250,000	144
Zinc	1,541	22,000*	no data*	14
Lead	648			34
Silver	1.728			12,700
Nickel	246	26,000	no data	106
Gold	0.250	200,000	>450,000	800,000

* Waste numbers for zinc, lead and silver are aggregated because these commodities are usually produced jointly

**Production numbers are for refined metals, unless stated otherwise

These figures however do not show the metal content of the waste. Several Material Flow Analyses (MFA) have been performed in order to quantify this aspect. Hatayama, Tahara and Daigo (2015) calculated the amount of metals left in the tailings and slag based on known process recovery rates and compared it to mine production for seven common metals. The Stocks and Flows (STAF) project initiated by Yale's Centre for Industrial Ecology also made a comparable study (Chen, W-Q & Graedel 2012). The results are summarized in Table 3.2.

Table 3.2: Global metal flows in mining estimated by two independent studies, Hatayama, Tahara and Daigo (2015) and the STAF project (Chen, W-Q & Graedel 2012)

Numbers are for year 2000 unless stated otherwise							
Hatayama, Tahara and Daigo (2015)	Iron	Aluminium (2002)	Copper	Zinc	Lead	Nickel	Silver (1997)
Mine production (kt/yr)	690,000	50,000	15,000	9800	3700	1300	20
Metals remaining in tailings and slag (kt/yr)	161,000	29,600	2200	2500	1100	373	6
Recovery rate	0.77	0.41*	0.85	0.75	0.71	0.71	0.7
STAF project	Iron	Aluminium (2006)	Copper (1994)	Zinc	Lead	Nickel	Silver (1997)
Mine production (kt/yr)	573,000	29,700	9610	6360	2740	1103	19.1
Metals remaining in tailings and slag (kt/yr)	120,000	7500	1550	1360	760	241	5.4
Recovery rate	0.79	0.75*	0.84	0.79	0.72	0.78	0.72

* There is a significant difference between the aluminium recovery rates determined by Hatayama, Tahara and Daigo (2015) and the STAF project, which is possibly due to a difference in the system boundaries chosen for the studies.

While some figures differ from one study to another, they however provide an order of magnitude for the amount of metals left in the waste. Unfortunately, these studies do not cover waste rock, nor do they distinguish tailings from slag. They also do not estimate the total volume of the waste and therefore provide no information on the metal concentration in mine waste. Another MFA from the STAF project (Gordon 2002) provided more detailed calculations on mine waste copper content in the USA, again not considering waste rock. Table 3.3 shows the results.

Table 3.3: Copper production compared with copper content in mining waste and in electrical wire in buildings, for the 1900 to 1999 period in the US (Gordon 2002)

	Total amounts (kt)	Copper content (kt)	Copper content (%)
Tailings	12,973,976	15,308	0.12
Slag	212,408	1256	0.59
Copper production	-	101,534	-
Copper content in electrical wire in buildings (largest stock of copper in use)		Discarded: 6603 kt	Still in use: 7520 kt

Gordon (2002, p. 15) compares these amounts to the amounts of copper discarded in post-consumption waste and concludes that “mill tailings are the single largest source of copper in waste deposits in the United States copper cycle”. However, the slag’s copper grade is much higher than that of the tailings.

The STAF project and the MFA from Hatayama, Tahara and Daigo (2015) are both top-down approaches, that is to say the amounts of waste were calculated based on production and process efficiencies data rather than direct data on waste generation. The reason is that production data are generally easier to find than waste generation data. Mudd (2014) on the other hand, directly compiled waste generation data in a bottom-up approach, which did not allow him to estimate the amount of minerals contained in the waste. In both cases, waste rock amounts remain mostly undetermined.

Waste rock generation from mining activities is often called a hidden flow (Brattebø et al. 2007). Brattebø et al. (2007) define hidden flows as material flows that do not enter in our economic system. Indeed, when thinking about the global human footprint one first thinks of all the material consumed by our society: consumer goods, infrastructure, food, fossil fuels etc. However, at the basis of all human activities much larger movements of materials are happening: the excavation of overburden in order to extract abiotic resources, but also the excavation of materials for the purpose infrastructure building (roads, buildings etc.), and soil erosion due to agriculture and forestry (more generally the extraction of biotic material). Unfortunately, because they are hidden flows and mostly do not bare economic value they remain largely unquantified.

3.2. A problem: the environmental impact of mine waste

Mining is a polluting and energy-intensive industry (Ayres 1997). Dudka and Adriano (1997) provide a useful overview of a mine's total environmental impact. Among these impacts, the pollution related to mining waste is particularly concerning as it impacts the local environment for centuries. Mudd (2013) adds that mine waste is "the Achilles heel of modern mining", because of the increased environmental risk it represents. This pollution can be in many forms such as dust carried by the wind, sediment eroded by water in waste rock dumps, or toxic seepage into ground waters or surface waters.

3.2.1. Acid Mine Drainage

Acid mine drainage (AMD), or acid and metalliferous drainage is a major pollution stream from mine waste. It consists in the oxidation of sulphide minerals in presence of water and oxygen, and results in these minerals dissolving in water, which becomes acidic and contaminated by heavy metals and other toxic elements. AMD is considered to be a major source of water pollution in countries that have historic or current mining activities (Simate & Ndlovu 2014), and one of the major environmental challenges the mining industry is facing worldwide (Hudson-Edwards, Jamieson & Lottermoser 2011).

Pyrite being the most common metal sulphide found in the earth's crust, it is also the main mineral involved in the AMD chemical reactions. In presence of water and oxygen, pyrite (FeS2) forms aqueous ferrous and ferric ions and releases hydrogen ions, which increases water acidity (Dold 2008). Similar reactions occur with other metal sulphides, which contribute to this acid release as well as heavy metal solubilisation and contamination (e.g. zinc, lead, copper etc.).

Acid mine drainage is a natural phenomenon of the rock weathering process, however, it is exacerbated and accelerated when the rock is moved and exposed as part of mining activities. In particular, waste rock dumps and tailings impoundments are often a primary source of AMD (Akcil & Koldas 2006), firstly because of the significant amounts of sulphide minerals it may contain, and secondly because the crushed material provides a larger surface area for the reaction to happen. Other significant sources are the mine voids, underground or open pit, where water tends to flow naturally and come in contact with un-extracted ore or remaining sub-economic material.

Mitigating AMD generation and the environmental pollution it causes is a particularly challenging task for miners as well as governments. Firstly, the true scale of the issue is hard to estimate, as many abandoned mine sites, where little information is available, contribute to ongoing pollution (Johnson, DB & Hallberg 2005). Secondly AMD prediction, which should occur before mining activities start, is also particularly challenging due to the complexity of the phenomenon and the unique character of each mine site (Akcil & Koldas 2006). Thirdly, while the chemistry involved in AMD generation is relatively well understood, its multiple consequences on the environment are difficult to quantify accurately, as Hansen (2004) shows. She dedicated her research to combining these impacts into one comprehensive impacted land indicator. Finally, once AMD is generated, its treatment is expensive (Kefeni, Msagati & Mamba 2017) and almost never entirely successful (Dold 2008). Quoting the results of a study on waste management practices in a Swedish mine site (Holmström et al. 2001), Dold (2008) concludes that "more and more long-term results show that oxidation cannot be prevented completely by geotechnical covers and wet cover systems" typically used by the mining industry to prevent the generation of AMD, and that in fact "they only slow down the process".

3.2.2. Mining legacies: an unquantified environmental hazard

The previous paragraphs showed that available data on mine waste generation is incomplete, and that the scale of the pollution caused by AMD is difficult to estimate. More generally, environmental legacies from past mining activities remain mostly unquantified.

A minimum of 50,000 recorded abandoned mines in Australia are to be added to the 500 operating ones (Unger et al. 2012). In the case of an abandoned mine, the provincial or state government becomes responsible for assessing the risks and prioritizing the sites that need the most maintenance or rehabilitation. The first step in managing abandoned mine sites is to gather them into an inventory. Sometimes this first step is not even achieved, and in Australia, one of the most resource-rich countries, the Northern Territory does not have such inventory (Unger et al. 2012). In the Australian states, inventories are mostly up-to-date, but do not provide many details on the sites except for their locality. These inventories were mostly made because of safety concerns. In one case, however, - in the state of Queensland - the abandoned mine dataset was also developed in order to document potential resources for future extraction (Unger et al. 2012).

Furthermore, there are regular reports of tailings dams accidents. Only recently, the Bento Rodrigues tailings dam collapsing in Brazil generated one of the country's biggest environmental disasters (Phillips 2015). Hudson-Edwards, Jamieson and Lottermoser (2011) estimated that over seventy major dam failures have occurred around the world since 1970. The International Commission on Large Dams reported 221 accidents occurring in the world from 1939 to 2000 (ICOLD 2001). This report covered all mined commodities, including coal and quarry minerals, and the seriousness of these accidents varies. About 60 of them involved an unwanted material release into the environment, the quantity varying from hundreds to several millions of cubic meters. The WISE Uranium project reported 85 accidents in mines (all commodities) between 1960 and 2017 (WISE 2015) that all involved uncontrolled release of material.

Moskowitz (2014) estimated that the USA had the highest percentage of tailings dam failures (39%) and that this was due to lax government regulations. Azam and Li (2010) made a review of the tailings dam failures occurring during the last hundred years and investigated both the cause of the accident and the social, economic and environmental impacts it generated. The concerning result is that for a great majority of accidents the total amounts of contaminants released remains unknown.

Finally, the spatial occupancy of mine waste is an important impact to consider. Mine waste covers hundred million hectares (Lottermoser 2010) and the land occupied is rendered unusable in the long term. The Fraser Institute (2012) identifies two main environmental-impact categories: the many contamination paths to the surrounding environment and the loss of productive land. Reid et al. (2009) and other Life Cycle Assessment practitioners argue that land use should be one of the most important impact categories in minerals Life Cycle Assessments.

3.2.3. Remediation and rehabilitation

The environmental damage caused by AMD began to be acknowledged by Australian legislations in the beginning of the twentieth century (Mudd 2013). They addressed the issue initially by banning tailings disposal in rivers. Later, in the 1970s, the growing scale of the environmental impact due to mine waste led to stricter regulations and governments started to require a rehabilitation program to be included as part of the mine planning. Nowadays, rehabilitation still represents a significant financial burden for mining companies. Nevertheless, they do need to comply with regulations and safeguard their reputation, which otherwise may tarnish and prevent them from developing new mining projects elsewhere (LPSDP 2016b). The Leading Practices Sustainable Development Program (2016) emphasises the need to implement progressive rehabilitation throughout the project's life cycle to minimise costs and increase the chances of success in the rehabilitation objectives.

These objectives vary from one site to another. In some cases, restoring pre-mining conditions may be achievable, or close to achievable. In other cases, the rehabilitation program has to be adapted to another predetermined post-mining land use, such as agriculture. The minimum requirement from the Australian legislation is that the mining operator demonstrates (through potential monitoring) that the rehabilitation program was successful in establishing safe and stable conditions on site before the mining lease can be relinquished, which would release the company from its liability (LPSDP 2016b).

Achieving successful rehabilitation may be challenging. It depends on a variety of aspects, including the composition and amount of excavated material as well as voids (in particular how susceptible they are to AMD), but also on the site's physical characteristics: its climate, the size and shape of the disturbed area, and the types of soil and rock (LPSDP 2016b). Additionally, the quality of rehabilitation may have high spatial variability due to heterogeneity in these different aspects, which generates uncertainty in monitoring results.

The decision of which rehabilitation options are preferred often involves complex trade-offs from one environmental impact to another. The work of Reid et al. (2009) illustrates well these trade-offs using a life cycle analysis. Reid et al. (2009) provide a comparison of six different mine closure scenarios. In this analysis, two options are considered for the management of tailings: they can be sent to a tailings storage facility or they can be partly used for the backfilling of voids in the underground workings. Three possibilities are then considered for mine closure to either remove or isolate the acid forming part of the tailings: submerging the tailings, partially desulfurizing and then covering with the desulfurized material, or covering with natural soils and re-vegetating on top. The results show that the options requiring more 'efforts', i.e. more machinery work, energy and material use, generate more environmental impacts in the short term. This is the case for backfilling and soil cover with re-vegetation. In the long term however, the options ranking is reversed when the benefits of improved soil quality compensate for this initial extra work.

Successful rehabilitation improves the quality of the local environmental, but also requires more external resources, and there can be a trade-off between direct and indirect impacts. In evaluating these trade-offs, the potential for re-mining the waste should be considered.

3.3. A resource: re-mining

While the environmental impact of mine waste is undeniably significant, there is an increasing body of research attempting to identify opportunities for mine waste. In this section, the various possibilities to make use of mining waste are discussed and analysed.

3.3.1. The distinction between resource and waste

Whether a material is considered as waste or resource depends on a variety of factors and the distinction between the two can sometimes be blurred. Some of these factors have already been introduced when discussing the variations in the efficiency or recovery and the consequent composition of the waste fraction in section 3.1. This section highlights three main categories of factors – time, the extractive strategy, and the economic context – , which all contribute to a waste material being converted to an economic resource.

3.3.1.1. Factor 1: Time

Time allows technological innovation to occur, which in turn allows for the economic extraction of minerals and metals from what were once sub-economic resources. Consequently, mine waste reprocessing is almost as old as mining itself. One historical example is the Broken Hill mining area in Australia, were zinc was initially not extracted, and the first twenty years of operations generated about 7 Mt of tailings grading 19% Zn (Mudd 2009). Technological advances, notably the invention of the flotation method, then allowed for zinc extraction and the tailings were reprocessed in 1905 (Mudd 2009).

In parallel, intensive mining has led to a continual decrease in ore grades over time (Gordon 2002)(see Figure 3.2). Ever increasing resource scarcity demands fast technological adaptation from industry to be able to keep mining economically the lower grade deposits and address these evolving challenges (Rönnlund et al. 2016a).

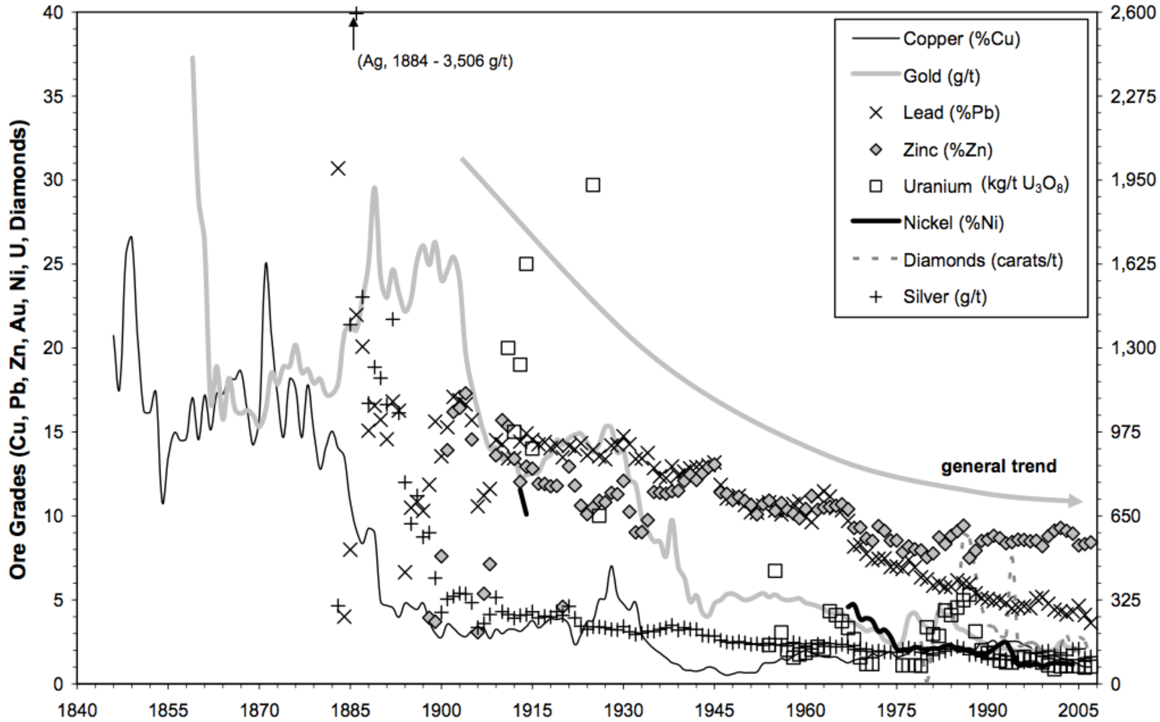

Figure 3.2: Combined average ore grades over time for base and precious metals, extracted from Mudd (2009)

Two conclusions can be drawn from this: firstly, because of technological advances, it is possible to re-mine mineral waste material that was not economic in the past, and therefore logically waste of today can become the ore of tomorrow. Secondly, taking into account the need for re-mining mineralised waste deposits may be necessary in a long-term vision of metal supply to society.

3.3.1.2. Factor 2: The extractive strategy

As seen in 3.1, the composition and the amount of mining waste rely heavily on human decisions, which are mostly based on economic considerations. The operating costs and the metal prices will be essential to adjust the cut-off grade that separates ore from waste rock, and the recovery rates that separate a mineral concentrate from tailings and leached ore.

In each mining stage, a part of the valuable metal being extracted is lost due to process inefficiencies. Other valuable materials are also lost because they are not of economic interest. For example, ore deposits usually contain several kinds of metallic minerals, and some valuable non-metallic minerals also often associate with them (e.g. fluorites and barytes)(White, DE 1968). However, they may not be present in sufficient amounts for their extraction to be economic, or their extraction simply does not align with the company's strategy or be part of its competencies.

Furthermore, metallic ore bodies present complex arrangements of minerals and the extractive strategy may, driven by economic considerations, result in recovering only some of the minerals, leaving the remainder to the waste fraction. The selected extractive strategy and plant design will define whether a particular type of mineral is to be treated as a main product, by-product or as an impurity. The statement from Wills and Napier-Munn (2006) "A valuable product in the 'wrong' concentrate will be considered as impurity" succinctly highlights this issue. In particular, poly-metallic ores are complicated to deal with and decision-making will have to consider trade-offs between the main product(s) and by-products recovery, taking into account operating costs and the operating challenges related to mineral extraction and processing. Again, not exploring the possibility to recover a particular by-product can simply happen because it stands outside of the company's core business focus.

Finally, optimising overall mineral extraction becomes more challenging when metallurgical processing and mineral processing are done by two different companies. A contract between the mine and the smelter defines the quality of the concentrate - i.e. sets acceptable levels of impurities and a minimum grade for the metal(s) of interest - and fixes its price. Sometimes, a smelter may extract more than one metal out of the concentrate and will pay for these additional metals if they are present above a certain grade, also set in the contract. This is typically the case for precious metals such as gold and silver found in copper concentrates (Wills & Napier-Munn 2006).

Hunter (2014) points out that these decisions, which are driven by profit maximisation, often do not result in optimal resource extraction.

3.3.1.3. Factor 3: The economic context

Finally, materials that were economic to mine may become waste because of an unplanned interruption in mining activities. The premature closures studied by Laurence (2011) and already highlighted in 2.1.2, often happen due to a drop in commodity prices, and leave some un-extracted resource behind. Temporary closings and re-openings are also common (Slade 2001), as mining companies may choose to halt operations and wait for an increase in commodity prices to restart them. However, an extended period of care and maintenance may affect the mine's economic and influence negatively the extractive strategy.

Mining projects are inherently limited in time by the extraction rate of the orebody. However, the macro-economic context as well as internal business decisions affect the project's economic viability and can either ensure or compromise the continuity of mining activities. Maintaining coherence in the extractive strategy despite a changing economic context in order to complete resource extraction and avoid sterilisation is a significant challenge for miners.

The line that differentiates waste and ore is therefore a dynamic and a fine one, and determined by factors that are more diverse than the pure physical properties of the material. However, according to Hunter (2014), mine operators in Australia have currently no interest or incentive in taking a closer look at waste material, considering possibilities to make value out of past waste, or anticipating for a potential future use for their own waste. Given the factors exposed above, and considering the need to address future resource scarcity, it is necessary to rethink the way waste is currently managed.

3.3.2. The R-words: terms and definitions

Edraki et al. (2014) distinguishes two cases for making use of the waste after its disposal: the reuse of the entire waste without further processing; and mine waste reprocessing in order to extract valuable materials. Lottermoser (2011) provides a larger classification, which includes the following R-words: re-mining, reprocessing, recycling, resource recovery and reuse.

In the context of mining reprocessing and recycling refer to the same activity of recovering valuable materials from mining waste through a new mineral processing stage. The term reprocessing may however be more appropriate to mining waste as it refers to material that has already been processed once - such as tailings and leached ore. Reprocessing would exclude waste rock, which is generated before mineral processing. Resource recovery is a more general term that may apply to any mineralised material.

Lottermoser (2011) defines re-mining as the extraction of resource from previously mined areas, e.g. re-digging an old pit. However, the term has been applied by other authors to mine waste, re-mining being the preliminary step of excavating material from the waste deposit in order to then send it to the processing plant. Re-mining may thus be used for any kind of mineralised waste (including waste rock) as well as for ore left behind from past operations. Moran et al. (2014, p. 10) use the term ‘new mining’, which is defined as “the recovery of metals from previous activities of inefficient mining and from waste materials resulting from the use of metals”. Note that outside the mining context Ayres (1997) also mentions waste mining, and defines it as using mineral processing technologies in order to extract valuable materials from other types of waste stream, such as electronic waste for example. In this thesis, the terms resource recovery, re-mining and reprocessing are used as defined in Table 3.4.

Table 3.4: Definitions of R-words used in this thesis

(Mineral) resource recovery	The activity of extracting and recovering minerals from any kind of mineralised material for them to be sold.
Reprocessing	Mineral and/or metallurgical processing of a mineralised waste material that has been already processed before. The term can be extended to waste rock, which went through a mining stage although not a processing stage.
Re-mining	The activity of excavating remaining mineralised material from a previously mined area of the ore, or from a waste deposit in the aim of recovering minerals from it.

Reuse of mine waste can be defined as providing a new function to the entire mine waste (Edraki et al. 2014). The term downcycling can also be used, as it conveys the idea of the low value of the bulk material compared to its more valuable mineral components. Examples of downcycling, re-mining and reprocessing, will be presented in the next section introducing the waste management hierarchy.

3.3.3. Towards a recovery-oriented mine waste management

Hansen (2004), who studied the environmental impacts of mine waste disposal, viewed solid waste deposits as an abiotic resource whose environmental impact is due to its non-utilisation rather than its depletion, and the quality of this resource, i.e. its grade, is declining over time through dispersion processes such as AMD. Hansen concluded that mine waste reprocessing may be desirable from an environmental perspective, as the minerals recovered will not contribute to local pollution, notably the degradation of groundwater resources.

Hansen (2004) thus provides a different perspective to mine waste management, where waste can be seen as a potential resource, and exhibits a certain kind of activity, waste re-mining and reprocessing that, unlike other extractive processes, may have a positive impact on the environment. Dold (2008) goes further, and provides a perspective of an alternative waste management system (Figure 3.3). The author replaces the term 'waste' by 'low-grade ore' and 'very-low-grade ore' and proposes the use of bio-leaching along with an impermeable base to collect the leachate in a long-term approach, until the leachate becomes economic to extract. The waste management system proposed by Dold (2008) makes the most out of the mineral resource present on the mine site by ensuring minimal waste. The author argues that mining will always be a destructive activity and its environmental footprint will continue to increase in the future, but optimising the extraction would reduce the footprint per unit of output, i.e. its eco-efficiency (see 2.2.3.3).

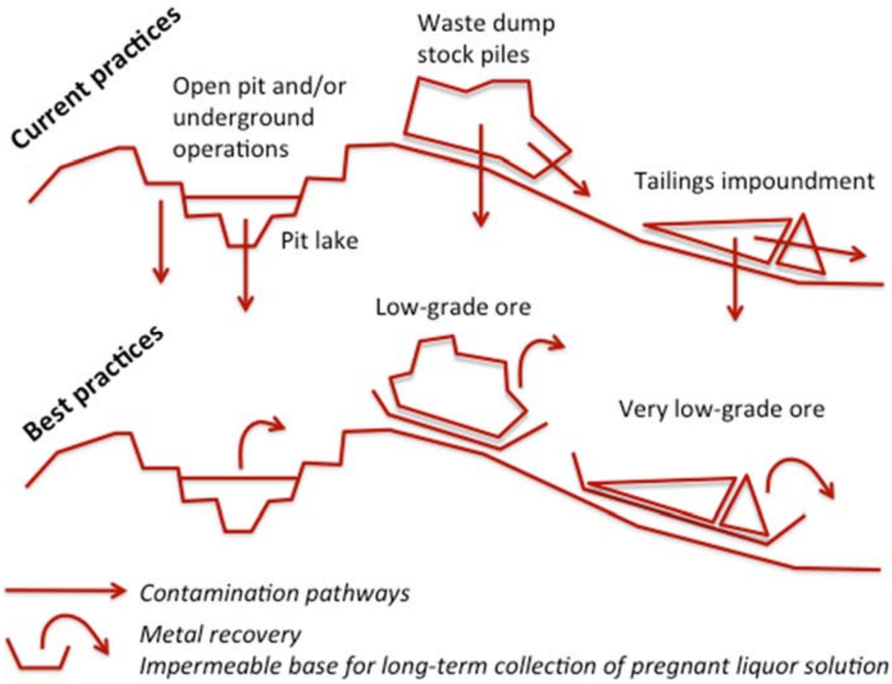

Figure 3.3: Viewing waste as a resource - a recovery-oriented approach to mine waste management. Adapted from Dold (2008) and extracted from Lèbre and Corder (2015).

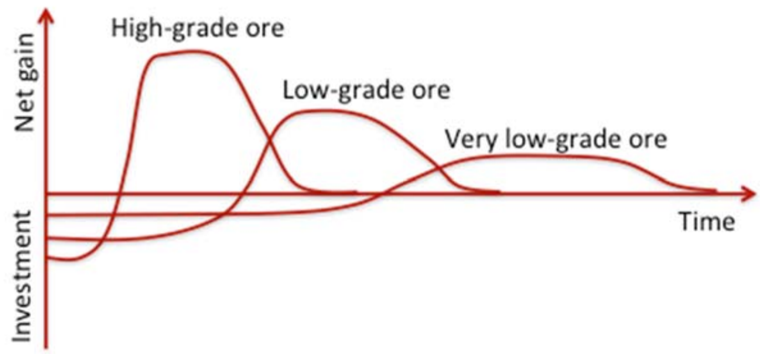

Figure 3.4: Increased lifetime and net gain resulting from a recovery-oriented mine waste management (extracted from Dold 2008)

Dold (2008) also shows how a recovery-oriented waste management such as in Figure 3.3 would result in a longer life of mine (Figure 3.4). However, Dold does not consider the economic stability issue raised by Laurence (2011), and a premature closure would go against efforts to maximise resource extraction.

This section provided a perspective that is possibly rarely thought of in the mining industry, that of a waste management that is actively aiming for resource recovery and value generation rather than a passive and permanent disposal. The main research question of this thesis asks how a recovery-oriented waste management such as the one sketched by Dold can contribute to improving the sustainability credentials of a metal mine. The first secondary research question then asks what characteristics such a waste management would have. The following section attempts to answer this question by going deeper into the idea proposed by Dold, and defining the general features of a recovery-oriented mine waste management system using a hierarchy of practices.

3.4. Development of the Mine Waste Management Hierarchy

The Mine Waste Management Hierarchy presented in this section was adapted from the commonly-used “reduce, reuse, recycle” (3Rs) pyramid to reflect the specificity of mine waste management. It prioritises waste management practices that maximise value making from waste material and recover its most critical components.

The 3Rs pyramid is commonly used in policy making, e.g. in the European Union (Hansen, W, Christopher & Verbuecheln 2002), and in Australia (DIIS 2016). It was primarily designed for post-consumer waste, as for example the term ‘reuse’ fits a type of waste that has already had a use phase, i.e. a discarded product. Likewise, the 3Rs pyramid places ‘reuse’ higher than ‘recycling’ because preserving the integrity and the function of a product is more desirable - and energy efficient - than tearing it apart to recycle its individual elements. The 3Rs pyramid is associated with the biological metaphor definition of industrial ecology, which emphasizes the need for circular material flows in order to reduce final waste disposal.

The 3Rs pyramid is also a core element of the New South Wales (NSW) Waste Avoidance and Resource Recovery Strategy (NSW EPA 2014) and consequently included in the Waste Management Plans (WMP) of NSW mining projects, such as the one for the Rasp mine (Boyle, P, Wilson & Jones 2012) and Dargues gold mine (Unity Mining Ltd 2013). In practice however, the WMPs reviewed tend to elude mining waste in the application of the 3Rs pyramid, and focus on other types of waste (e.g. discarded tyres) generated within the mine site. These WMPs usually only acknowledge the need to minimise all types of waste and do not propose concrete strategies to prevent, reuse or recycle mining waste.

Even if WMPs were to include mining waste in the general waste management strategy, applying the 3Rs directly to mining waste would lead to inconsistencies due to the specificity of this kind of waste. If reuse is considered superior to recycling because the absence of a reprocessing stage would save energy, water and other resources, this does not take into consideration the minerals contained within mining waste, and which - under certain conditions - justify the use of additional resources for their extraction.

Hence there is a need to clarify and define what the priorities are for the management of mining waste. These priorities include the need to mitigate waste-related environmental impacts, as well as the loss of valuable and scarce minerals. The Mine Waste Management Hierarchy (MWMH) developed as part of this thesis differs from the 3Rs pyramid essentially by redefining and switching the ‘reuse’ and ‘recycle’ terms (see Figure 3.5). ‘Recycling’ is replaced by ‘reprocessing’, which refers to the extraction of further ‘resource ingredients’; and ‘reuse’ is replaced by ‘downcycling’, defined as making use of the entire waste material for a certain application. Downcycling may or may not require an initial treatment or ‘processing’ stage, but does not include mineral or metallurgical processing per se.

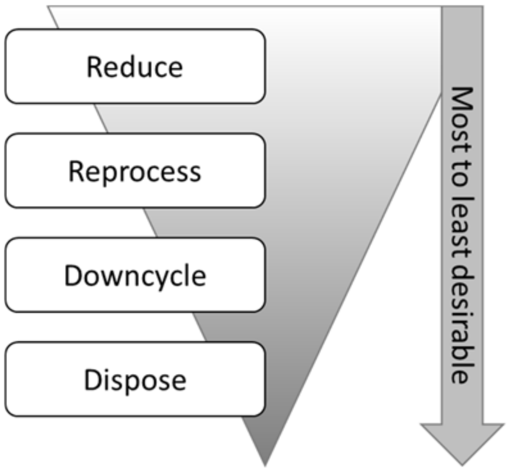

Figure 3.5: The Mine Waste Management Hierarchy. Extracted from Lèbre, Corder and Golev (2016)

In this section, the four elements of the hierarchy are presented and are based on reviewed public data from mining companies as well as the academic literature. This illustrates the hierarchy with concrete examples and shows how it fits with current waste management practices, available technologies, and recent advancements in research. This section ends with a discussion about the applicability of the Mine Waste Management Hierarchy, informed by the work from previous academic research.

3.4.1. Reduce and prevent

First in the priority list, 'reduce' can be expressed in different terms, e.g. 'source reduction', as in U.S. EPA (1994), 'waste prevention' (Lottermoser 2011), or again waste avoidance (Bian et al. 2012). Preventing waste prior to its generation is considered as the most desirable option, not only for mining waste but for any kind of waste. However, in the case of mining waste it is the most difficult to achieve (Bian et al. 2012), and also the least documented, as there is currently very little economic incentive for mining companies to consider waste prevention objectives in initial mine planning (Laurence 2011).

At the outset, waste prevention needs to be defined for mineralized mining waste. Preventing waste, i.e. reducing waste generation, cannot be defined as simply reducing its tonnage or volume. In the context of resource scarcity, it is also about minimising the loss of the ore's valuable components, the target metals, and minimising the dissemination of contaminants from waste to the surrounding environment. Sulphide minerals in particular may fit both categories, having sometimes both economic value and environmental significance. Indeed, sulphide minerals remaining in mining waste and in contact with water and air may generate acid mine drainage, the main environmental problem of contemporary mining activities (Dold 2014). Though reducing volume and tonnage of mining waste is also relevant from a land use perspective, waste prevention measures should in particular focus on the metalliferous minerals that have economic and/or environmental significance.

The examples of waste prevention below all have in common a focus on increasing the efficiency of mineral extraction from the ore body, i.e. the resource efficiency - an expression employed by Laurence (2011) - or more precisely ‘mineral resource efficiency’.

Waste prevention is different for mining waste compared to other kinds of waste. In other sectors waste prevention, i.e. reduction of the unwanted output, is closely related to a decrease in the input (e.g. the concepts of dematerialization or sustainable consumption, in Lèbre (2012)). In the case of mining, it is not desirable to reduce the mineral input. Reducing the amount of ore being mined may lead to the remaining ore being sterilised and the un-extracted minerals being lost. At the mine site level, the goal is to optimise ore extraction in a way that minimises mineral losses at every stage and over the life of mine. A consequence of this increased mineral recovery would be a reduced need to open new mines in green fields, which constitutes a significant environmental benefit.

The first example of waste prevention at the mine site level is ‘avoiding high grading’, which is strongly related to the concept above. This example is represented in Figure 3.6 as a circled ‘a’, and it occurs at the mining stage in the definition of the extractive strategy, notably the cut-off grade. Choosing a high cut-off grade in a short-term vision of profit making would result in shortened life of operations, and a significant part of the mineral resource may be left behind and potentially sterilised (Laurence 2011).

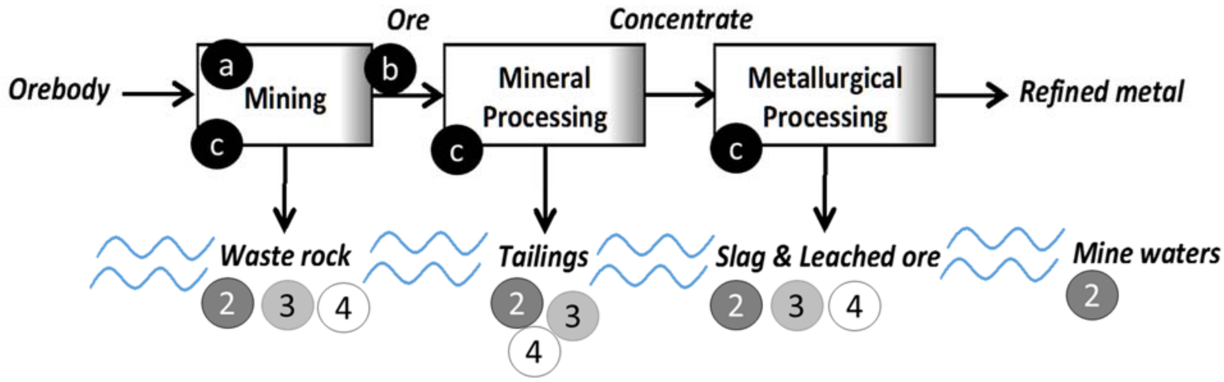

Figure 3.6: Positioning of the waste management activities within mining operations. Notes: a - avoiding high grading; b - pre-concentration methods; c - by-product recovery, corresponds to prevention activities; 2 - corresponds to reprocessing; 3 - to downcycling; 4 - to responsible disposal. Figure extracted from Lèbre, Corder and Golev (2016)

Pre-concentration methods, noted 'b' in Figure 3.6, add an additional process of ore sorting, which aims at reducing the amount of barren material that enters beneficiation (Norgate & Haque 2013). This results in an increased mineral processing efficiency, potentially reduced energy and water requirements (Gunson et al. 2012; Norgate & Haque 2013) and possibly enhanced mineral extraction. Pre-concentration technologies offer a means to mine and process material more efficiently by a more precise characterisation and selection of the material, which provides opportunities to optimise production. This optimisation, however, depends again on human decisions, which may still adopt a high-grading strategy. Pre-concentration methods applied with the aim of maximising mineral recovery may result in an increase in the overall waste rock tonnage, due to higher amounts of barren material being discarded. Notwithstanding, waste prevention as defined in this thesis would still be achieved.

In practice, sorting technologies developed by companies like Minesense (MineSense 2015) and TOMRA (TOMRA 2016) are emerging. Older applications can also be found: the on-line X-ray analyser at the Doe Run Fletcher mill was already being used in the 1990s (U.S. EPA 1994). The use of this sorting technology allowed reducing significantly the volume of slag being generated as well as the amount of metals being lost in tailings (U.S. EPA 1994).

A third example of prevention is by-product recovery (noted 'c'), where a combination of technologies allows for the selective recovery of the main mineral and its by-products. A significant example is the Lead-Zinc-Silver mine of Broken Hill, Australia, which extracts copper as a by-product at grades comparable to tails grades (about 0.12% according to

Mudd (2009)). At the Olympic Dam mine in Australia, copper and uranium is recovered from flotation tails prior to tailings disposal using a combination of flotation, leaching, solvent extraction and electrowinning and flash furnaces (BHP Billiton 2009). This relatively complex process flowsheet contributes to recovering three by-products – gold, silver and uranium - and increases the recovery rates of the primary metal, copper.

In particular, because of its implication in acid mine drainage, recovering pyrite as a by-product prior to waste disposal can be seen as a successful example of waste prevention. In 1986, the Magma Copper Company's Superior mine added a pyrite flotation plant (U.S. EPA 1994). Although the additional revenues generated by selling the pyrite products were not significant for the company, this activity was considered useful as it generated less reactive tailings, thus avoiding some of the waste treatment costs associated with the likely future acid generation.

In the academic literature however, there are only a few examples of waste prevention that emphasise potential environmental benefits. Kazadi Mbamba et al. (2012) and Broadhurst et al. (2015) show that acid mine drainage can be prevented by removing the sulphide minerals prior to waste disposal, again by flotation. However, both papers do not consider the possibility of making value out of the sulphide-rich material. Struthers (1999) proposes continuous stirred tank reactor bioleach stage to extract non-strategic target metals, including the potentially toxic ones (e.g. As, Cd, Sb and Th), other mineral products (e.g. fluorspar or mica), and other by-products (e.g. sulphuric acid and ferrous sulphate).

More generally, technological innovation at every stage of mining operations is key to increasing the efficiency of the extraction from the ore body and thus minimising waste in the early stages. At the mineral and metallurgical processing levels, technological improvements can range from a small change to conditions in existing processes (e.g. use of a more efficient reagent), to the addition of processing stages (e.g. additional flotation plant for by-product recovery), and to the choice of an entirely new processing technology. The choice of the right technology or the right combination of technologies that achieves the highest rates of waste prevention is however limited by technological advancement at the time (Bian et al. 2012). Therefore, if waste cannot be prevented at the time of disposal, a second potential option is to re-process it in the future, in order to achieve a waste reduction over the life of mine.

3.4.2. Reprocess

Waste reprocessing is the second priority in the Mine Waste Management Hierarchy. Indeed, waste reprocessing may provide the same advantages as waste prevention, i.e. enhanced mineral recovery and pollution mitigation, however with an inherent time delay due to the storage of the waste. During this period of storage, some acid mine drainage may have already occurred and some minerals irreversibly lost. It also means waste management related environmental impacts were not avoided, such as land use, energy and infrastructure requirements.

One of the most common technologies related to waste re-processing in the academic literature is bioprocessing, either in a bioreactor (e.g. Sánchez-Andrea et al. 2014; Ucar et al. 2011) or directly within the waste deposit (e.g. Dold 2008; Peek, Barnes & Tuzun 2011). Phytomining is another technology of interest (e.g. Alcantara et al. 2015; van der Ent et al. 2017; Wilson-Corral et al. 2011), as well as ion exchange resins (e.g. Hansen, HK et al. 2013; Romão, Gando-Ferreira & Zevenhoven 2013). In practice, a few examples of mineral waste reprocessing can be also found in mining companies' sustainability reports (e.g. Xstrata 2009, 2011).

Various factors may encourage a company to reprocess its own or another company's waste. Reprocessing may be done to recover a previously overlooked companion metal whose market price increased significantly (Macri 2015). In South Africa, Ergo reprocessed 171.6 million tons of tailings, because of the high tonnage they represented and because grades within the tailings could be determined with higher certainty than those of the deep-level underground exploration (Ergo Mining Ltd 2008). At Ernest Henry Mining, Queensland, tailings are being reprocessed for magnetite as a result of additional capacity of the process plant (Xstrata Copper 2012). The report indicates that magnetite comprises 20% of the tailings volume, which would therefore be significantly reduced. Struthers, Brumley and Taylor (1997) evaluated that reprocessing may be attractive to mining companies where there is pre-existing reason to excavate the waste, e.g. the material needs to be relocated for environmental concerns (Garling 2015) or underground backfill requirements.

A small number of 'scavenger' companies dedicated to mineral waste reprocessing are emerging, putting forward their technical expertise, e.g. Magnetation, USA, uses a magnetic separation technology (Magnetation 2016). BioteQ, Canada, uses a combination of sulphide precipitation and ion-exchange technologies (BioteQ 2016). Ecologix, USA, uses physico-chemical processes involving flocculation and sedimentation (Ecologix 2016). Tetronics, UK, uses a plasma process (Tetronics 2015). Frazer Alexander, South Africa, and Jet Mining, Australia, are involved in waste re-mining projects where they use hydraulic high-pressure jets to dislocate compacted tailings (Garling 2015; Jet Mining 2016).

In some gold mines such as Mount Morgan, Australia, unwanted copper-cyanide complexes may form during the mineral processing stage, causing an over-consumption of cyanide and decreased recovery rates for gold and silver (Alonso-González et al. 2013). Another “scavenger” company - Carbine Resources - proposes to reprocess tailings in Mount Morgan using ion-exchange resins to recover copper sulphate prior to gold recovery, and thus increasing revenues from both copper sulphate sale and increased gold production (Carbine Resources 2017). Carbine Resources’ strategy provides a good example of waste minimisation making value out of disregarded by-products and contributing to site remediation, as it is also planning to recover pyrite for sale. Carbine Resources’ project is in that respect similar to the case of waste prevention at the Superior mine in Arizona (see above), except it will take place on an already heavily impacted site after nearly three decades of abandonment. The Carbine Resources project at Mount Morgan analysed and discussed in more detail in Chapter 5.

3.4.3. Downcycle

Waste properties may not allow for forecasting any future reprocessing, i.e. metal concentrations are too low to justify the extra resources (energy, water etc.) needed for reprocessing. In this case, opportunities for downcycling may be considered.

Downcycling refers to using the bulk of the waste material for a ‘low’ purpose, that is to say a purpose that generates low value compared to the value of the metals that could be produced by reprocessing the waste. Although downcycling shows advantages as it reduces the amount of waste that needs to be disposed and its related environmental impacts, reusing the bulk material means losing irreversibly the remaining minerals it may contain. The Leading Practices Sustainable Development in Mining (LDSDP) report by the

Australian federal government acknowledges that downcycling options that make mineral recovery from tailings uneconomic are to be discouraged (Laurence et al. 2011).

The LDSDP report uses the example of backfilling. Backfilling an underground mine is one of the most common examples of downcycling (Lottermoser 2011). Mt Isa Mines (Xstrata 2011) reported that out of the 12.4 million tonnes of tailings produced in 2011, 3.5 million tonnes were used as backfill.

Several authors studied the use of cemented paste backfill, a mix of tailings, water and small amounts of binder (e.g. Bouzalakos, Dudeney & Chan 2013; Fridjonsson et al. 2013; Wu et al. 2015). Backfilling is often necessary for safety reasons (notably by filling voids), and Coussy et al. (2012) points out that it can also allow to access and mine more ore as it stabilises the underground installations. Therefore, backfilling can increase resource recovery from the ore body, which is desirable as part of the general aim of minimising mineral losses at the mine site level.

However, backfilling does not make waste disappear. Johnson (2003) underlines that underground mineralised and permeable material may come in contact with groundwater, and acid mine drainage may occur underground just as much as at the surface level. It was the case at the abandoned underground mine Mount Lyell, Tasmania (Koehnken 1997). Although several authors argue that the cemented paste backfill mix is saturated in water and therefore more stable (e.g. Cihangir et al. 2012; Coussy et al. 2012; Desogus et al. 2013), the AMD potential is not eliminated. It is therefore important to avoid using highly reactive material in backfilling and use inert material for this purpose.

Other downcycling cases at the mine site level include producing fill, sealants and embankment material to contain other waste and contribute to site rehabilitation (Struthers 1999). Construction materials are also popular for downcycling of mining waste. Mill tailings have been used to manufacture blocks and bricks, and metal rich material has been used for glass and rock wool production (Edraki et al. 2014; Struthers, Brumley & Taylor 1997). In general, downcycling uses usually require the presence of a local market, as their low value does not allow long-distance transportation (Struthers 1999).

Another application that is extensively investigated in the literature is the use of mining waste for carbon capture and storage (e.g. Assima et al. 2014; Bodénan et al. 2014; Hall et al. 2014) (Meyer et al. 2014; Veetil et al. 2015). Carbon storage by mineralisation could be a potential option for CO2 emissions mitigation. This is performed by carbonating a particular mineral or chemical within the waste, e.g. magnesium hydroxide. When the source of magnesium hydroxide is mining waste, it is possible to store carbon within the waste deposit, and Hitch and Dipple (2012) demonstrate the financial feasibility of integrating carbon storage by mineralisation into a nickel-sulphide mine. Romão, Gando-Ferreira and Zevenhoven (2013) also takes an interesting perspective as they combine the extraction of magnesium hydroxide for future carbonation with the extraction of other minerals from mining waste.

3.4.4. Dispose responsibly

Once all possible uses for the waste material have been considered, then safe disposal may complete the Mine Waste Management hierarchy. Mine waste disposal techniques have made some progress in recent years. In particular, compared to conventional tailings slurry disposal method, the paste, thickened or filtered tailings provide significant environmental advantages by allowing recovery and reduction of water consumption, extending tailings dam capacity and often improving stability of disposed materials (Caldwell & Charlebois 2012; Kotiranta et al. 2015). However, other authors have pointed out that none of the existing disposal methods can prevent acid mine drainage and other toxic seepage totally (e.g. Bian et al. 2012; Dold 2008; Hansen 2004; Struthers 1999). Hence, ideally, permanent disposal suits only a material that is chemically inert, and for which no economic use could be found.

However, it is likely that either temporary or permanent disposal will still be necessary. Temporary disposal, or rather stockpiling, is a required step prior to waste reprocessing. It may also be a required step prior to downcycling, especially in the case of on-site underground backfill, sealing and embankment applications that have to be performed at a particular time of the mine’s life.

Techniques that may be suitable for permanent disposal do not necessarily represent good stockpiling alternatives. For example, waste treatment and disposal methods that aim at isolating, diluting, encapsulating or neutralising reactive material (e.g. covering methods, co-disposal or surface treatment of minerals) might make the material less accessible and future reprocessing more costly and less efficient.

On the contrary, stockpiling requires segregating the material in a way that anticipates for its future use. Depending on the intended use – reprocessing and/or downcycling - segregation can be done in various ways: by particle size, target metals concentrations, waste stream source, mineral types, time of generation etc. At the same time, this means the reactive material may remain exposed, and during the stockpiling period acid generation may occur, resulting in both pollution and irreversible mineral losses (LPSDP 2016c). Such trade-offs have to be considered given the expected length of the stockpiling period (see 3.4.5).

Pro-active control of acid mine drainage during the stockpiling phase may constitute a partial solution. Installing leachate collection systems in waste deposits is a way to both control seepage and potentially collect metal-rich effluents for reprocessing. Indeed, many authors propose to recover metals directly from AMD waters (e.g. Chen, T et al. 2014; El-Ashtoukhy & Abdel-Aziz 2013; Sánchez-Andrea et al. 2014; Sun et al. 2015). Dold (2008) proposes to place acid generating waste on top of an impermeable layer from which the leachate can be collected. Seepage interception could be combined with in-situ bioleaching, which would accelerate the natural oxidation rate to facilitate future reprocessing. However, leachate collection systems are not totally effective and a significant fraction of AMD may still escape (Wels, Findlater & McCombe 2006).

3.4.5. Discussion on the application of the Mine Waste Management Hierarchy

Minerals Engineering International (MEI) Online provides an extensive and indicative list of papers published on environmental issues related to mining (MEI 2015). It constitutes a representative summary of current research in the area. Publications referenced by MEI were reviewed and classified for the 2011-2015 period, in order to analyse how different elements of the proposed Mine Waste Management Hierarchy (MWMH) are represented and reported in the academic literature (Table 3.5). The areas covered by these papers showed a dominance of two main topics: mining technologies applied to waste recycling further down the value chain (e.g. post-consumer waste) and AMD mitigation. Downcycling and reprocessing are less well-represented topics but they still account for close to 17% of all the papers.

Table 3.5: Representation of the MWMH in the academic literature.

Topic	No overlap	Overlap with AMD mitigation	Overlap with downcycling	Total*
Mining technologies applied to downstream waste	73	N.A.	N.A.	73
Reprocess	21	17	10	45
Downcycle	23	13	N.A.	46
Reduce	0	2	0	2
AMD mitigation	38	N.A.	13	70

* In total, 268 papers gathered by Minerals Engineering International on environmental issues, years 2011 to 2015, were analysed.

Waste prevention, however, is almost not represented. The reason is possibly that efficiency/productivity measures are not considered, both by the authors and the reviewers, as an environmental issue. The analysis also reveals a reasonable number of papers that cover more than one topic, showing recognition that reprocessing, downcycling and AMD mitigation have the potential to be combined together for greater benefits.

Indeed, the elements of the hierarchy presented above are not mutually exclusive and the MWMH should be considered holistically, jointly with the need to mitigate the mine's environmental impact and ultimately rehabilitate the mine site. As seen earlier, the most common downcycling options usually require the material to be benign. In her thesis, Struthers (1999) proposes a recycling system that combines reprocessing of mining waste with downcycling options and rehabilitation. Because every mine site is unique, the recycling system is meant to be designed on a case-by-case basis and adapted to the physical, chemical and metallurgical properties of the waste. In designing the flowsheets, the author also takes into account external factors such as the local demand for downcycled material, and ends with demonstrating the economic feasibility of the concept. The reprocessing stage creates new value by extracting metal and decontaminating waste at the same time, which makes the remaining material benign and available for downcycling applications. Tetronics in the UK, already mentioned in 3.4.2, proposes to adopt a similar philosophy (Tetronics 2015).

Struthers's recycling system follows the MWMH. Although her analysis is applied to existing tailings, the author emphasizes that the greatest potential for this recycling system lies in future mines, i.e. by realising waste prevention. Integrating this system into mine planning would allow designing mining operations around the aim of maximum resource utilisation and maximum metal extraction. This is notably important as AMD is not only a waste related issue is also generated by exposed minerals in mining voids.

Although this analysis provides encouraging results, the positive impact of implementing such a recycling system needs to be demonstrated quantitatively on the overall sustainability performance of a mine site. This is especially true as a trade-off may occur between the goals of maximising resource utilisation from waste and reducing other resources consumption such as energy or water. A range of criteria and benchmarks can be determined to assess whether a particular waste stream should be prevented, reprocessed, downcycled, stockpiled for a certain period, or permanently disposed. Useful sustainability frameworks exist that take into account in particular the criticality of the potentially extractable minerals as well as total resource use (Azapagic 2004; Rönnlund et al. 2016a; Spuerk, Drobe & Lottermoser 2016) and thus allow making an informed decision.

Finally, a barrier to the successful implementation of the Mine Waste Management Hierarchy is the uncertainty of mining projects with changing economic conditions (Laurence 2011). Mining projects' economic viability is influenced by changes in commodity prices, and premature mine closures may ruin the efforts towards maximising resource extraction. A way to better manage the sometimes unavoidable interruptions over the mine's life is by keeping records of mine waste generation, composition and location, and transferring that knowledge to potential future reprocessing projects. More comprehensive waste characterisation data are necessary for a greater number of waste reprocessing projects to become economically feasible, as it can offset exploration costs for new deposits.

3.5. Conclusion

This chapter reviewed mine waste management and showed that the difference between waste and ore is often a relative, time-dependent, and man-made distinction rather than based on physical and unalterable limitations. However, the general perception within the mining industry is that waste management and rehabilitation are an economic burden. This chapter showed that proactive approaches that maximise resource utilisation and value generation from waste while mitigating its environmental impact exist, and need to be prioritised over final disposal. Furthermore, increasing mineral extraction and resource utilisation from existing mine sites, be they operating or already closed/relinquished, would reduce the need to open new mines on virgin lands.

The proposed hierarchy sets an order of priority for waste management practices. Its elements are not mutually exclusive, and the greatest environmental and economic benefits will come from well-thought combinations of these elements. To better support decision-making, the Mine Waste Management Hierarchy needs to be an integral part of a comprehensive framework that encompasses all material flows within a mine site.

It is critical that such a waste management strategy should be implemented not only on a particular mining project but also with consistency throughout the entire life of the mine, from the initial ore discovery to the final closure of a fully rehabilitated site. Furthermore, the optimisation of resource recovery from waste can only be done effectively with the optimisation of resource recovery from the entire mine site, ore body included.

The expression ‘recovery-oriented mine waste management’ is the subject of this thesis’ main research question. Secondary research question a) also asks what main characteristics this waste management should follow. This chapter allows drawing a general definition of what a recovery-oriented mine waste management is:

- Firstly, it is one that follows the Mine Waste Management Hierarchy, by prioritising resource recovery over final disposal;
- Secondly, it is one that is integrated spatially and temporarily within the mine site and the mine’s life cycle in a way that all material flows are optimised to minimise waste and maximise resource efficiency.

Following chapters explore how this integration could be put in practice.

4. Development of a methodology for a case study analysis

There is a variety of sustainability frameworks either adaptable or specifically designed for the mining industry. These frameworks, originating from academia, governments and industry associations, are attempting to comprehend the contribution mining can make to sustainable development. Rather than proposing a new framework to add to the list, this thesis focuses on the main identified gaps in existing frameworks, and attempts to build a more stable foundation that can support further research.

As shown in Chapter 2, a key element is the mineral resource itself, a resource that is finite and non-renewable. Several authors (e.g. Ayres, Ayres & Råde 2002; Fonseca, McAllister & Fitzpatrick 2013; Laurence 2011) argued that most mining sustainability frameworks tend to overlook this aspect, although it is what makes the extractive industry's role in society unique. This role will be key for the mining industry's contribution to sustainable development.

The five capitals framework (Porritt 2003) includes the mineral resource in the natural capital. The mining industry enables a transfer from this capital to the four other capitals (in particular the manufactured capital, but also the financial, human and social capitals). The question is: how effective is this transfer? At the mine site level, how much of the mineral resource is being effectively extracted and utilised, and how much is left behind? The previous chapters showed that there is evidence that a significant part of the resource is left behind as waste, sub-economic material or sterilised resource.

The remaining chapters in this thesis investigate these questions using case study mine sites. The methodology adopted for the case study analysis and the fieldwork is presented in this chapter. Section 4.1 first presents the general structure of the methodology, which is articulated around three main levels, and two case studies. Section 4.1 starts with setting a frame for the methodology, with theoretical considerations in subsection 4.1.1. Sections 4.2, 4.3 and 4.4 then present each of the three levels, providing both a theoretical rationale and a structure for the investigations to be undertaken at each level. Section 4.2 presents the material flow indicators developed to characterise the metabolism of a mine at the mining project level. Section 4.3 describes the qualitative investigation to be undertaken at the life-of-mine level. Section 4.4 focuses on the last level, which is the policy incentives, and explains the approach taken in corresponding Chapter 7. Finally, section 4.5 provides practical information on the methodology for the fieldwork, i.e. the adopted approach to collect the data necessary for this three-level analysis.

This chapter combines ideas from two papers published as part of the thesis research, Lèbre and Corder (2015) and Lèbre, Corder and Golev (2017a). Although most of these ideas were rephrased for the sake of coherence within the chapter and within the overall thesis, several direct quotations remain.

4.1. Main structure of the methodology

Before presenting the methodology adopted to the analysis of the case studies, to which chapters 5, 6, and 7 are dedicated, section 4.1.1 makes an important distinction between the mining project and the mine's life cycle. The distinction is central to the analysis of the case studies, and these two elements form two of the three levels of the methodology. The three levels are presented in 4.1.2. Section 4.1.3 then moves to presenting the two case studies chosen and explaining why they are well-suited for the analysis.

4.1.1. The mining project versus the mine's life cycle

In integrating mine waste management within the mine's overall metabolism, the life cycle of the mine and the life cycle of a particular mining project needs to be differentiated. Sometimes, several mining projects take place on the same mine site at different periods of the mine's life. This raises the question of the effect of premature closures, as well as interruptions or transition periods between two projects, and how this influences resource recovery or losses. Sometimes, only one project takes place and coincides with the mine's life cycle, and its closure corresponds to the end of the mine's life. In this case, it should be ascertained that none of the remaining material on site would become economic to mine in the foreseeable future. Figure 4.1 distinguishes three different scenarios that encompass the possible cases.

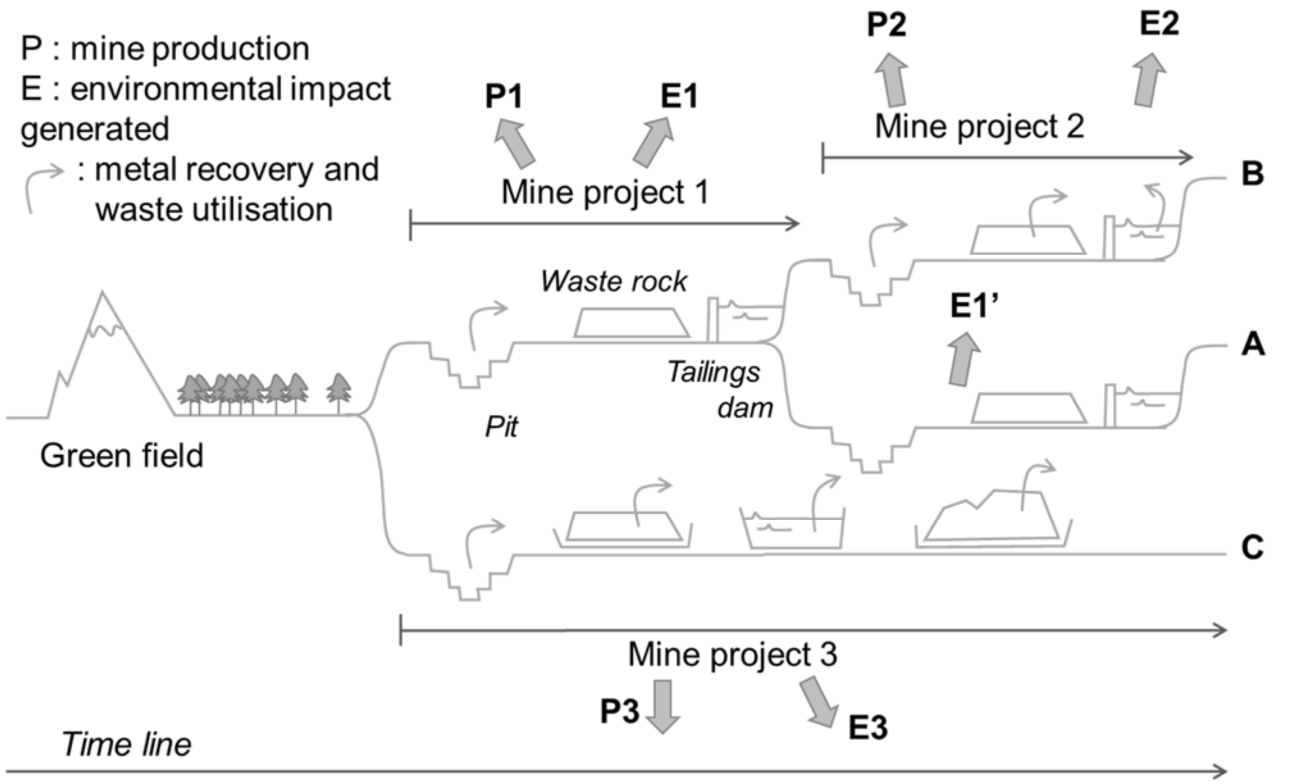

Figure 4.1: Three different scenarios. Adapted from Lèbre and Corder (2015). Distinguishing three scenarios to be compared. Scenario A: traditional mining; scenario B: re-mining and re-processing; scenario C: preventive and recovery-oriented waste management.

Scenario A represents a traditional mining project that generates a certain production P1 while having an environmental impact E1 during its entire life. After closure, environmental legacies E1′ remain. E1′ varies depending on site conditions and on how successful rehabilitation was, if rehabilitation was undertaken.

In scenario B, a certain time after its initial closure the mine re-opens for another mining project. The new operator reprocesses some of the waste deposits and/or re-mines parts of the ore body that were left behind. This second operation leads to an additional production P2 and generates an environmental impact E2. The two operations are separated by a period of interruption, and the mineralised material - ore body, low-grade stockpiles or mining waste - left on site from project 1 is not stored in a way that anticipates for a possible future extraction.

Scenario C presents a hypothetical mine site that is operated continuously with a planning for future recovery, similarly to Dold's proposal (2008) (see 3.3.3). In this scenario, waste management is an inseparable part of the extractive strategy, which integrates practices of waste prevention and reprocessing. The project operates during a certain period, longer than in scenario A and without discontinuation as in scenario B, with a total production P3 and a total environmental impact E3, which includes post closure legacies.

Ideally, production figures P1, P1+P2 and P3, and environmental performances E1+E1', E1+E2 and E3 of scenarios A, B and C respectively (and their "eco-efficiency", i.e. P/E ratio), would be compared quantitatively to evaluate the effect of both higher resource recovery and better planning for future extraction.

To compare these scenarios A and B essentially means evaluating project 2, the re-mining project. Due to project 2, scenario B provides an enhanced resource recovery compared to scenario A. It however requires additional inputs and generates an additional environmental impact while in parallel treating, partially or entirely, the legacy from project 1, i.e. E1′. A quantitative analysis can aim at determining whether such a project, be it a waste reprocessing project or a traditional mining project targeting remaining ore material, is beneficial with regards to both the recovery of the mineral resource and the environmental performance of the mine.

It should be noted here that project 2 takes place on a "brown field", a site already heavily impacted by previous mining activities, rather than being implanted in an untouched "green field". Furthermore, the minerals extracted in a re-mining project could feasibly substitute in the market the minerals that would be extracted in a hypothetical new green field mine. Hence, minimising the mine site's overall environmental impact (E) is not the goal. The goal is to minimise the environmental impact embedded in metals, that is to say maximise the P/E ratio of a mining project, and of the overall mine's life cycle.

The difference between scenario B and scenario C is also uncertain. E3 could potentially be smaller than E1 + E2 — the total environmental impact generated by scenario B — as better planning and the continued activity allowed for a cleaner disposal of the low-grade material. Furthermore, the discontinuation between mine projects 1 and 2 may result in abandoned infrastructure that could have been reused if it had been properly maintained. The new infrastructure carries embedded environmental impacts that contribute to E2. P3 could also potentially be higher than P1 + P2 as a consequence of this better planning and the resulting efficiency improvements and cost savings. Also, project 2 initially needs a prospection stage in order to determine the composition of mine waste, while project 3 has monitored its low-grade stockpiles.

4.1.2. Three levels of investigation

In practice, comparing quantitatively scenarios A, B and C is challenging. The research in this thesis has been designed in a way that takes into account potential constraints and limitations.

Firstly, defining and quantifying E in a meaningful and aggregated manner is in itself challenging. As discussed in Chapter 2, Life Cycle Assessment is an appropriate modelling tool, however it suffers from methodological limitations, in particular because it is a standardized tool that has rarely been applied at the mine site level (Norgate & Haque 2010). Secondly, if an LCA or other systemic environmental impact analysis were to be conducted, it would require the three selected case studies for scenarios A, B and C to have an initial similar deposit in order to make them comparable. Considering the high variability and unique character of ore deposits and mine sites in general, this would be equally challenging. Thirdly, scenario C is an ideal scenario, hence finding a representative case study that resembles it is also difficult.

To overcome these difficulties, the methodology for the analysis of the case studies was designed around three levels of investigations, which integrate the initial mine waste management level explored as a desktop study in chapter 3. These three levels are represented in Figure 4.2.

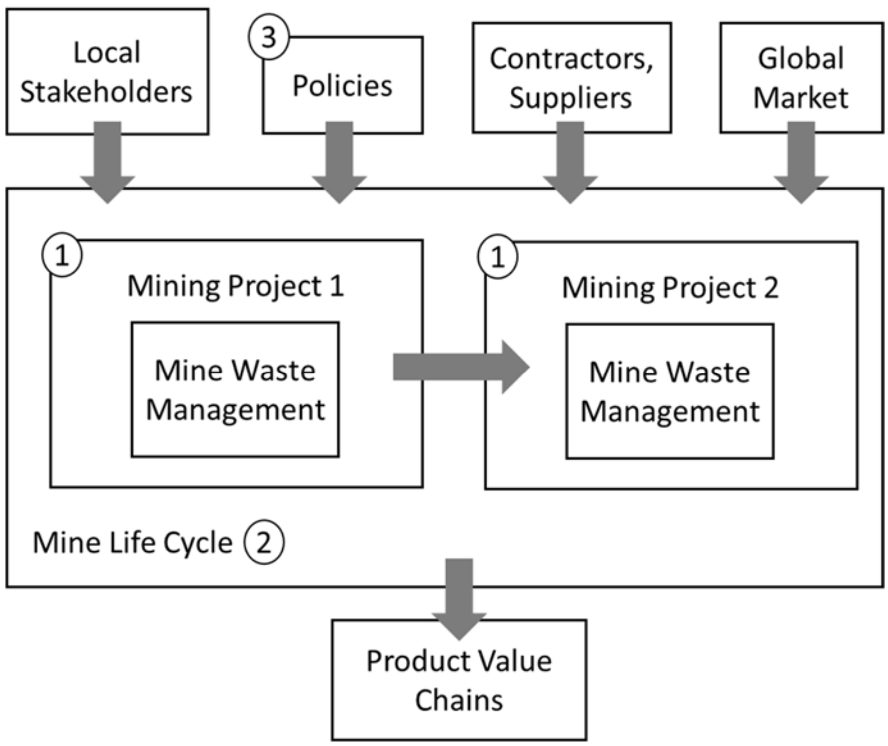

Figure 4.2: Three levels of investigations: mining project (chapters 5 and 6), mine life cycle (chapters 5 and 6), and policy incentives (chapter 7), encompassing the mine waste management level (chapter 3)

As discussed in chapter 3, recovery-oriented waste management practices need to be integrated within the overall extractive strategy of a mining project. Therefore, the metabolism of a mining project needs to be investigated closely.

For this first level, Material Flow Accounting (MFA) indicators were designed to investigate quantitatively scenarios A and B, and are presented in 4.2. These indicators are applied to a specific mining project, and characterise the performance of its extractive strategy with regards to the overall resource available on site, e.g. how much resource recovered compared to how much is lost in the waste stream, or left behind at the end of the project. The effect of mine waste management practices such as prevention, reprocessing, and downcycling on the flows of mineralised material within the mine site are quantified with the MFA indicators. In particular, these indicators allow evaluating projects 1 and 2, and the potential benefits of project 2 compared to a permanent mine closure. They can be applied to existing mining projects, be they past, current or prospective, as long as sufficient data are available.

As discussed in 4.1.1, mining projects need to be observed as part of the mine's overall life cycle. This second level, presented in 4.3, observes qualitatively how the mining projects fit within the entire life of the mine, and investigates the effect of transition periods and interruptions between two mining projects. The mine life cycle perspective also allows understanding how past waste management practices affect the extractive strategy of a new project (e.g. whether it allows for the economic reprocessing of waste). This provides some findings as to the life cycle inefficiencies that make scenario C potentially beneficial compared to scenario B.

A third level builds on the findings from the mining project and mine life cycle levels to investigate how external incentives can help move mining practices towards scenario C, or towards a scenario B with more coherent and organised transitions between projects. There are various external factors that influence both the individual mining project and the mine life cycle, in particular:

- The local community: principle 9 of the ICMM principles emphasises the importance of securing the social licence to operate, understanding that conflicts with the local community may compromise the project’s viability. Hence, a mining project should “contribute to the social, economic and institutional development of the communities in which it operates”.
- Local and national governments influence mining projects from the approval stage to the closure. They are also involved in the overall mine’s life cycle during which they sometimes intervene directly, from the first exploration and ore discovery stages to the final lease relinquishment. Depending on the country, governments have various degrees of authority on the mining company’s environmental, social and economic performances.
- The global market has a clear influence on the economic viability of mining projects, which is affected by price fluctuations and the demand for the different mining products.
- Contractors and suppliers are external stakeholders that intervene throughout the mine’s life cycle. There is a wide diversity that may provide various expertise, products and services, but their influence is to some extent managed by their costumer, which may be the mine operator itself or in some rarer cases the government.
- Finally, the mine is connected to the rest of the metal value chain via the metallurgical processing stage, which may or may not take place on the mine site. The contract with the downstream costumers of the mine determine the properties of the mine’s products.

It was chosen to focus on policy incentives, as governments have a particularly essential role to play in the context of this thesis. They are involved at both the mining project and the mine life cycle levels, having both the authority and an interest in prolonging mining operations and preserving the national natural resource (see 4.4). They may also to a certain degree have an influence on the other external stakeholders.

4.1.3. Two case studies

The gold mine Mount Morgan in Queensland, and the copper mine Mount Lyell in Tasmania, are the two case study sites that were examined in this thesis. Both have hosted more than one mining project throughout their life cycle.

Mount Morgan and Mount Lyell were chosen as they are prime candidates for testing the research questions of this thesis and had sufficient quality data to calculate the MFA indicators. Both sites are well known in Australia’s mining history and significant amount of publications report on the sites histories, allowing the gather sufficient data for the past operations. However, it was necessary to collect data from present or future mining projects taking place on the sites, and both the current Copper Mines of Tasmania (CMT) project in Mount Lyell and the future Carbine Resources project in Mount Morgan were willing to assist with this. Additionally, the possibility of visiting the two sites and meeting representatives from both the mining and governmental sides allowed for the collection of further valuable information.

Common characteristics to the sites are that they are both historical sites where operations started at the end of the 19th century, and they both exhibit particularly concerning environmental legacies due to acid mine drainage. They presented the opportunity to understand the evolution of mining practices over the past century, as well as to study the particular relationship with local governments, who pay a closer attention to these two sites of economic, environmental and historical significance.

4.2. Level 1: Material Flow Accounting indicators

A set of Material Flow Accounting (MFA) indicators was developed in order to study – at the mining-project level – the metabolism of a mine. Such metabolism is characterised by flows and stocks of bulk mineralised material and of its mineral content, and includes, among others, flows and repositories of waste material. This section describes the process that led to the development of these indicators, and provides details on the final MFA indicator set that is to be applied to the case studies.

Meaningful indicators for comparing scenarios A, B and C are the production P, the environmental burden E, and the ratio P/E, i.e. the eco-efficiency of the mining project. The environmental burden E should encompass all life cycle impacts, including direct environmental impacts generated on site (pollution due to toxic waste generation, greenhouse gas emissions due to fuel consumption, etc.) and indirect environmental impacts embedded in energy and material use (e.g., the materials used to build the process plant were extracted from another mine, transportation in and out of the mine site also generates greenhouse gas emissions, etc.).

Production P can be defined in numerous ways. It can be the amount of mineral concentrate produced, or its mineral or metal content, either expressed in a physical unit or monetary unit. It can also be the amount of ore extracted during the mining process, or fed to the process plant. Other relevant flows that can be accounted for in a production indicator are the flows of material moved as part of mining activities but not contained in the final product: bulk amounts of waste rock, tailings and other wastes, and their mineral or metal content, expressed in either physical or monetary value. Estimations of the initial mineral resource stock, i.e. the size and composition of the ore deposit, as well as variations of this stock throughout the mine's life cycle may also be taken into account. These flows and stocks can provide information on the efficiency of production, as they allow for the comparison of how much is produced and how much is left behind, or with how much effort it took, since any movement of material requires energy and other resources. This relates to the definition of productivity touched upon in 2.2.3.3, i.e. outputs per unit of inputs (Steen 2014).

Note that production and environmental impact may be closely related, as for example movements of bulk material are associated with energy use for its transport and processing, water and chemical use for its processing, and land use for its disposal. Minerals lost during mining operations may both have an economic impact (as a sterilised resource) and an environmental impact (with the possibility to contribute to contaminated drainage).

Eco-efficiency links production to environmental footprint, and gives an estimate of the efficiency of the extractive process, ensuring that resource recovery is not favoured at the expense of the environmental footprint. Its calculation depends on the choice of P and E, which will lead to different significations.

Aggregating all production and environmental impacts criteria into one indicator is challenging, and not necessarily useful as it would hide relevant information, while a set of indicators may help obtain a clearer view. It was therefore chosen to develop a set of indicators that exhibit different aspects of ‘P’, ‘E’ and ‘P/E’.

Eurostat, the statistical office of the European Union, developed a methodology using indicators for economy-wide material flow accounts (Eurostat 2001), which have been adapted by Sendra, Gabarrell and Vicent (2007) to be applicable to industrial areas. Using the accepted approaches of the Eurostat methodology and the work of Sendra, Gabarrell and Vicent, a set of indicators was specifically designed in this thesis for a mine site, which can be seen as a particular case of industrial area. These indicators focus on flows and stocks of mineralised material within the mine site, with an emphasis on either reversible or permanent mineral losses. The set aims at enabling comparison between mining projects, in order to help identify strategies that contribute to minimising mineral losses and optimising mineral resource utilisation.

Table 4.1 lists the indicators, their definitions, and their possible correspondence with Sendra, Gabarrell and Vicent’s indicators.

Table 4.1: Material Flow Accounting indicators set

#	**Mine site MFA indicator**	**Unit ***	**Definition and comments**	**Correspondence to Sendra, Gabarrell and Vicent (2007)**
1	Total Production (TP)	$	Aggregated production of all extracted commodities	Corresponding indicator is expressed in tons
2	Total Production from Waste (TPW)	$	Production with waste material as the feedstock	No equivalent indicator

3	Total Material Processed (TMP)	t	Total material entering process plant throughout the project's life	Equivalent to Direct Material Input
4	Total Material Moved (TMM)	t	Total material moved in order to extract the processed material = TMP + waste rock	Equivalent to Total Material Requirement
5	Net Waste Generation (NWG)	t	Total waste generated – Total waste processed (e.g. case of tailings reprocessing)	Equivalent to Total Wastes Generation
6	Mineral Losses to New Waste (MLNW)	$	Aggregated estimates of mineral content in waste generated by a particular mining project (excludes irreversible losses)	No equivalent indicator
7	Total Mineral Losses to Waste (TMLW)	$	MLNW – TPW (New losses – Recovered losses)	No equivalent indicator
8	Material-Efficiency (ME)	$/t	Total Production / TMM	Similar to Eco-Efficiency
9	Extraction Inefficiency (EI)	%	MLNW / (Total Production + MLNW). TP +MLNW represents the Total Mineral Resource contained in the feedstock	Similar to Material Inefficiency
10	Irreversible Mineral Losses through Dumping (IML-D)	$	Minerals lost in uncontrolled dumping of waste material.	No equivalent indicator
11	Irreversible Mineral Losses through AMD (IML-AMD)	$	Minerals of interest lost in acid leakage. From field estimations. Can be calculated for a particular time period (e.g. 20 years)	No equivalent indicator
12	Resource Left Behind (RLB)	$	Un-extracted material from the ore body	No equivalent indicator
13	New Area Impacted (NAI)	ha	Total virgin land area impacted by a particular mining project	No equivalent indicator

* Monetary unit used for all MFA calculations is US$.

Figure 4.3 below shows each indicator's position within the mine site system. As can be seen in Table 4.1, some indicators are expressed in monetary units (i.e. US dollars) and are representative of the mineral content of a certain flow, while others are expressed in tonnes and represent movements of bulk material. Ratios of two or more indicators express a certain aspect of efficiency. Indicator 13 is the only indicator that does not relate to minerals or mineralised material, but represents the overall environmental footprint of the mine in terms of geographical area.

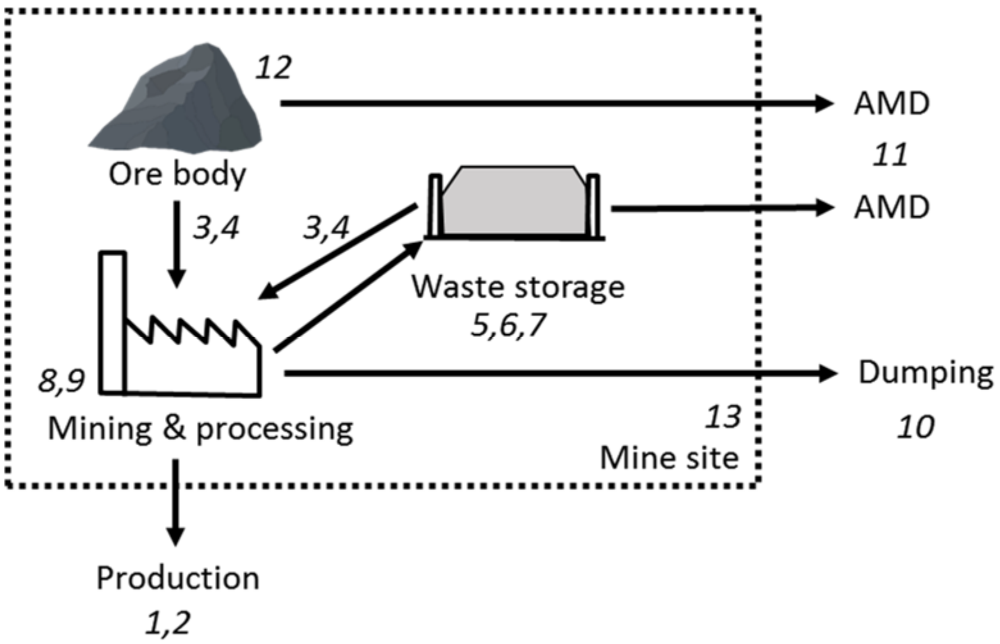

Figure 4.3: Material Flow Indicators positions within the mine site metabolism

Details on each indicator are presented below. The initial set applied on Mount Morgan did not include indicators 10 and 12, which were identified during the second case study of Mount Lyell. Unlike Mount Morgan, Mount Lyell is characterised by significant waste dumping practices and un-extracted resources in the ore body. The MFA indicators were therefore refined and adjusted based on the outcomes of each case study, and used to compare mining projects in terms of their waste generation, waste utilization and mineral losses that occur at different stages of the mine's life.

4.2.1. Initial set

This MFA indicator set aims to provide a common basis for comparison between mining projects. All indicators are aggregated over the lifetime of a mining project, which means that in the case of Mount Morgan, the indicators are calculated for each of the three mining projects. However, some indicators may also be presented on an average yearly basis by dividing them by the number of years of operations, in the aim of providing further information on the size of the operations, e.g. the capacity of the processing plant, and the equipment requirements for the transport of ore, waste and final product(s). This is done notably for Total Production (TP), Total Material Moved (TMM) and Total Material Processed (TMP).

The following indicators are calculated using monetary units (US dollars):

- Total Production (TP)
- Total Production from Waste (TPW)
- Mineral Losses to New Waste (MLNW)
- Total Mineral Losses to Waste (TMLW)
- Irreversible Mineral Losses through AMD (IML-AMD)
- Irreversible Mineral Losses through Dumping (IML-D)
- Resource Left Behind (RLB)

Monetary units are regularly used by practitioners, both industrial and governmental, to sum up different commodities such as gold and copper (e.g. ABS 2016; Newcrest 2016). These monetary MFA indicators are therefore expressed here as the sum of the commodities produced or lost (in tons) weighted by their individual prices (in US$/t). This allows for aggregation of figures into a smaller set of indicators, in the case of mining projects extracting more than one commodity. Furthermore, using monetary units allows weighing the commodities by their actual market value. For example a mining project may extract 2 t of gold and 2 Mt of pyrite concentrate, but gold, being a much more valuable commodity than pyrite, remains the primary commodity extracted (Eurostat 2001).

As production and mineral losses indicators should represent the amounts of minerals that are either recovered or lost, given prices should be used for each commodity. In this sense, commodity prices act as weighing factors, rather than have an economic value. This allows for comparison between projects that occurred in different years.

Total Production from Waste (TPW) is non-zero for projects that are reprocessing mineralized waste to extract further valuable components. TPW quantifies the value of minerals that were lost in the waste stream during past operations and are now successfully extracted. On the contrary, Mineral Losses to New Waste (MLNW) corresponds to the minerals that are not recovered during the waste reprocessing stage. Because of process inefficiencies some of the minerals present in the waste material input are therefore lost a second time in the “new waste” output (tailings and slag). TPW + MLNW represents the total mineral value of waste being reprocessed.

However, Mineral Losses to New Waste may be calculated regardless of whether the project is using ore or waste as input. For projects processing virgin ores, the “new” waste is simply the waste generated by initial mining and mineral processing (i.e. tailings, but also waste rock, see below for an explanation on waste indicators). MLNW represents the mineral content of the waste being generated.

Total Mineral Losses to Waste (TMLW) is equal to MLNW minus TPW, and accounts for the minerals that are recovered through a waste reprocessing activity. While Mineral Losses to New Waste is representative of the efficiency of the extraction process, regardless of whether the feedstock is ore or waste, TMLW distinguishes projects that have a waste reprocessing activity. Connecting these indicators to the waste hierarchy presented in Chapter 4, MLNW relates to waste prevention through more efficient extraction, whereas TMLW takes into account both waste prevention and waste reprocessing.

Irreversible Mineral Losses through AMD (IML-AMD) quantifies the value of minerals that are lost in water flowing through mineralised material and ultimately from the mine site, if no measure is undertaken to control that flow. IML-AMD are irreversible and permanent. Determining accurately the IML-AMD of a mining project will be more challenging than for the other indicators. Firstly, IML-AMD is not directly related to upstream human processes as Mineral Losses to New Waste and Total Mineral Losses to Waste are. AMD is a natural phenomenon, and in order to predict its impact groundwater flow modelling is necessary. As the impact of AMD varies over different time periods, it is more difficult to estimate, and means that an appropriate time period needs to be determined for the IML-AMD indicator. This makes it difficult to attribute IML-AMD to a particular mining project if more than one project took place on the same site. Finally, when a water flow modelling study is performed on the mine site, and AMD losses are estimated accurately by the daily AMD water flow and its chemical composition, usually the only minerals reported are the ones considered as contaminants (e.g. copper, zinc, arsenic etc.). Possible metals of interest such as gold and silver are typically not reported in the AMD water composition.

Bulk material indicators, Total Material Processed (TMP), Total Material Moved (TMM), and Net Waste Generation (NWG), are equivalent to Direct Material Requirement, Total Material Requirement and Total Wastes Generation in the Material Flow Accounting (MFA) terminology respectively (see Sendra, Gabarrell & Vicent 2007). TMP is the amount of material - ore or economic mineral-bearing waste - that directly enters the mineral processing plant. TMM is the total amount of material moved as part of the mining process to access the economic resource (ore body). Therefore, TMM is equal to TMP plus waste rock and overburden. NWG represents the total waste generation of a mining project, but does not include the amount of waste that is being reprocessed, in the case of waste reprocessing activities. Therefore, a mining project that processes exclusively waste has a NWG close to zero, or even negative, because the waste generated already existed prior to the project.

The Material-Efficiency (ME) indicator is the ratio between production and Total Material Moved. ME is similar to Eco-Efficiency as defined by Sendra, Gabarrell and Vicent (2007). More generally, Eco-Efficiency was defined in chapter 2 as the ratio of production over environmental impact. TMM is representative of some, but not all, of the environmental impacts generated by the mining project. TMM is a broad indicator that quantifies the total movement of material within the mine site, including pit formation and waste generation. TMM is therefore related to the land use, energy requirements to move the material as well as the sources of pollution through AMD.

The Extraction Inefficiency (EI) is a percentage that represents the total losses that occurred during the mining project (Mineral Losses to New Waste) divided by the mineral content of the input material, which is by mass balance equal to the mineral content of the total output MLNW+TP. EI is calculated regardless of whether the project is processing ore or waste and solely indicates the quality of the extraction strategy. EI is similar to the

Material Inefficiency indicator developed by Sendra, Gabarrell and Vicent (2007), except the ratio of the inputs and 'outputs to nature' in Sendra's indicator is expressed as tonnes of bulk material, whereas EI here is a ratio of the mineral value (expressed in monetary units) contained in the bulk material. The EI indicator does not include IML-AMD as these losses occur further downstream of the extraction process.

The notion of impacted area is difficult to define, as shown in the work from Hansen (2004), who dedicated a thesis to this particular impact category. For the purpose of this thesis, the evaluation of the New Area Impacted (NAI) is more straightforward compared to Hansen's work. NAI, in hectares, represents the geographical area impacted by mining activities (open pits and other voids, waste deposits such as waste rock piles, tailings dams, but also areas covered by infrastructure). Areas that are successfully rehabilitated may be discounted from NAI. However, NAI is contained within the mining lease and does not include possible widespread AMD impacted area outside the mining lease. The latter would be relevant to estimate as part of the overall environmental footprint of mining activities. However, determining this area would be a complicated task, requiring an extensive flow modelling analysis (of both underground and surface water), which is too complex for the aims of using indicators. Although it does not estimate the entire impact caused by AMD, the IML-AMD indicator does provide a useful indication of mineral losses due to AMD relative to the mine's environmental impact outside of the lease area.

NAI distinguishes green field projects from brown field projects. For mining projects that take place in a brown field (i.e. in the case of a mine reopening), their NAI may be equal to zero, if their activity does not extend beyond the area impacted by the previous mining project(s).

4.2.2. Refined set

From the initial MFA indicator set developed at the time of the Mount Morgan case study, two indicators were added in order to take into account two particularities that distinguish Mount Lyell from Mount Morgan: Irreversible Mineral Losses occurring through waste Dumping (IML-D), and non-waste Resource Left Behind (RLB).

Mount Lyell presents a significant amount of remaining un-extracted gold and copper resources - silver is not reported as part of the 2016 mineral resource potential assessment from Geological Survey Tasmania (MRT 2017). Mount Lyell is also characterised by the extent of its waste dumping practices, contributing significantly permanent mineral losses. The Total Mineral Losses to Waste indicator includes Irreversible Mineral Losses through Dumping losses, which means some of the TMLW losses are non-recoverable. TMLW less IML-D provides the value of minerals in waste remaining on site.

The definition of Extraction Inefficiency also needed to include Resource Left Behind as the sum of Total Production, Mineral Losses to New Waste and Resource Left Behind represents the total mineral resource contained in the original ore body. EI = (MLNW + RLB) / (TP + MLNW + RLB).

The final set is thus made of thirteen main indicators, with the possibility of adding annualised ones by dividing the indicators by the number of years the project lasted.

4.2.3. Additional relevant indicators

Except for the New Area Impacted indicator, all indicators in the set developed above provide information on flows and stocks of mineralised material (either of the bulk amounts or of their mineral content) within or leaving the mine site. However, there are other indicators that could be added in order to comprehend both the mine's entire environmental footprint and mining projects' production.

The total environmental footprint of the mine encompasses all emissions to the environment (solid, liquid and gaseous), and all resource uses (e.g. water, land, energy, chemical reagents etc.). Each emission may cause a specific environmental impact, and each external resource used carries another embedded impact. From a production perspective, emissions and resources use are also seen in terms of inputs and outputs to the mining and mineral processing stages, which relate to the mine's productivity, by definition the outputs per unit of input ratio (Steen 2014). Hence, knowledge of these flows would allow quantifying P and E more accurately, weighting the useful outputs, i.e. the products, against the unwanted outputs (waste and uncontrolled emissions), and separating clearly the mineral resource input from the other inputs needed for mineral resource extraction.

Therefore, other indicators developed in Sendra, Gabarrell and Vicent (2007) would be relevant to add to the set:

- Total Water Input (t),
- Total Energy Input (GJ),
- Energetic Intensity (GJ/t),
- Worker productivity (t/worker).

The indicator framework developed by Rönnlund et al. (2016a) also includes indicators related to chemical use, greenhouse gas emissions, and land use of mining activities.

These indicators provide additional information that would ensure potential trade-offs are properly understood, e.g. that the objective of maximising mineral recovery is not done at the expense of other non-renewable resource use, or does not result in an unacceptable increase in greenhouse gas emissions.

Although relevant, these additional indicators were not included in the analysis of the case studies in Chapters 5 and 6. The choice of focussing on mineral resource flows within the mine site was made because these flows are both an essential and yet overlooked sustainability dimension in the mining industry. This thesis places the mineral resource at the centre of the mine site's metabolism, from which other flows can then later be built on. The main reason for not including these indicators was the lack of data. If included, the indicator set would require substantially more data, which, for the mining projects in Mount Morgan and Mount Lyell and especially for the past projects, was often incomplete or missing.

Another relevant indicator not included in the study is a downcycling indicator. Downcycling is part of the waste management hierarchy presented in chapter 3, and it would be worth including the amounts of bulk material used for different purposes inside or outside the mine. The reason for not including this indicator in the case study analysis is that the documentation for both Mount Morgan and Mount Lyell did not record any of these downcycling flows.

4.3. Level 2: Qualitative investigation throughout the life of mine

Level 2 of the analysis of the case studies aims to comprehend the entire life of the mine, from initial discovery of the orebody to the present time, but also considerations into the potential future of the mine. This section provides a deeper analysis at what are the key aspects that define the continuity of the life of a mine, and describes the approach taken for the analysis of the case studies.

There are two components to the qualitative investigation presented in case study chapters 5 and 6. One is retrospective, and looks at how past events have contributed to enhance mineral losses. The other is prospective, and looks at how the current situation within and surrounding the two case study mines is either enabling or disabling potential future mineral recovery and environmental remediation projects.

- Retrospective investigation: restoring continuity in the life of mine

To complement the MFA indicators that are applied on mining projects, this investigation looks at the entire life of the mine, from the discovery to the present moment, paying closer attention to the gap between two projects.

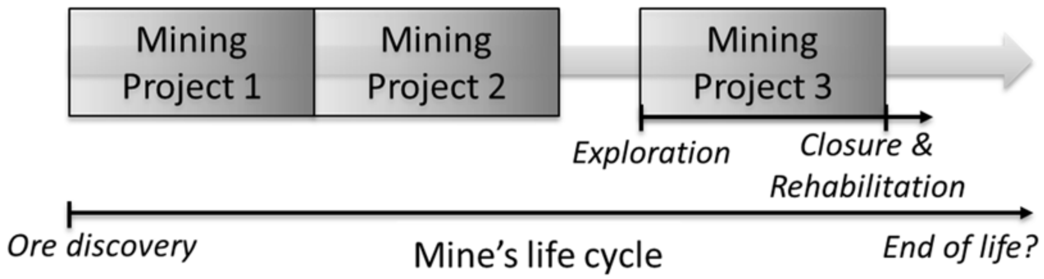

Figure 4.4: The mine's life cycle. Extracted from Lèbre, Corder and Golev (2017a)

Figure 4.4 presents a timeline for a hypothetical mine's life cycle that comprises three mining projects. The transition between the first two projects is continuous (e.g. this can occur due to a change in ownership), whereas mining activities are interrupted for a few years between project 2 and 3. In theory, a mining project commences with an exploration stage and finishes with a closure stage. However, depending on how the transition between projects 1 and 2 is achieved, one or both of these stages may be avoided.

The existence of more than one mining project on site raises the question of how discontinuities in mining operations may affect the optimisation of resource extraction, as well as the consistency and success of environmental remediation. For example, the exploration stage may be facilitated by past information on the site. The supposedly permanent closure stage may need to be rethought to take into account possible future reopening.

The example in Figure 4.4 is not uncommon, especially when the ore deposit is large and complex. Besides, mines often close as a result of a drop in commodity prices (Laurence 2011) to reopen later when the economic environment becomes more favourable. Slade (2001) estimates that in well-explored regions, initial openings and final closings of mines are significantly less common than temporary closings and re-openings.

Any interruption in activities – if not consistently planned - may lead to temporary or permanent loss of mineral resource. If the interruption is extended in time, as it is in the case of a premature closure, the site is likely to be left without a planning for extraction of the remaining resource, and the site rehabilitation is not complete, due to lack of time and means. In addition to these economic and environmental drawbacks, extended interruptions may impact negatively all stakeholders involved (for instance employees, local businesses and communities, contractors and customers etc.), therefore impacting the mine's social performance.

Discontinuity in the mine's life cycle is the main difference between scenario B and scenario C as presented in 4.1.1. This investigation should provide preliminary findings on how scenario C could be achieved and what would be its advantages compared to scenario B.

The retrospective investigation makes use of the qualitative historical data from the two case study sites as well as interviews during the sites visits, and identifies the events in the mine's life that may have contributed to inefficiencies in the extractive process and thus to mineral losses. This includes interruptions and transitions periods, but also practices and events occurring during the mining projects (e.g. change in ownership, waste management practices, high-grading strategy etc.). This investigation thus makes a connection with the MFA results and incorporates them within the overall mine life cycle, adding qualitative information that was not encompassed by the MFA indicators.

- Prospective investigation: SWOT-like discussion

The second part of the qualitative investigation observes the current situation in the two case study sites and examines the future possibilities. Both mine sites exhibit certain barriers and enablers that either facilitate or constrain the development of a future waste reprocessing business or more generally the prolongation of mining operations, which could enhance resource extraction and potentially mitigate some of the environmental legacies.

The Strengths – Weaknesses - Opportunities – Threats (SWOT) analysis was used for this investigation. In a SWOT analysis, the project needs to be clearly defined and the objectives specified, in order to then identify the internal and external factors that are favourable and unfavourable to achieve these objectives. Strengths are internal to the project, and are assets in favour of achieving the objectives; weaknesses are internal and unfavourable; opportunities are external and favourable; Threats are external and unfavourable. Such tool provides a simple frame to gather and organise qualitative information on a project and identify sources of potential future difficulties as well as ways to counteract them.

The focus of this analysis is a potential future mining project taking place on the case study site, and the objective would be the prolonging of mining operations in a way that enhances resource recovery while addressing past, mine-waste related environmental impacts, thus contributing to improving the site's sustainability performance.

This methodology was applied to both sites with some room for flexibility: in Mount Morgan, Carbine Resources is the selected future project to study and apply the SWOT analysis, while in Mount Lyell, with Copper Mines of Tasmania currently on care and maintenance and with no responsibility towards environmental remediation, there is no appropriate project for the SWOT to be applied. Hence, the analysis for Mount Lyell focuses mainly on external opportunities and threats, with fewer considerations for strengths and weaknesses. Therefore, this part of the investigation is called a 'SWOT-like' discussion rather than a 'SWOT analysis'.

4.4. Level 3: Policies for new business models in the mining industry

Level 3 of the methodology for the analysis of the case studies focuses on policies. This section provides reasons for investigating the government as a key stakeholder in influencing mining practices. It then describes the approach taken to observe its involvement in the selected case studies.

From the literature review, it appeared that the government role was often critical in influencing mining practices, and this was later confirmed during the site visits. This role is particularly relevant in the context of this project. Mining companies have a commitment to shareholders to maximise profits and, while efficiency measures and a longer lifetime might result in increasing benefits, there is little incentive for the operator to extract and recover more than what it judges economically desirable at the time. In general terms, mining companies have economic drivers that are focussed on maximising their revenue rather than necessarily maximising resource utilisation.

Unlike most industries, the mining industry's main input - the natural resource - is not purchased, and as a result any resource left behind as waste, as un-extracted ore, or as sub-economic material, does not directly affect the mine's profit. Royalties are a mechanism that governments use, as the owners of the resource, to companies pay for the resource they are extracting. However, royalties are output-based, that is to say they are calculated based on the quantity produced, and not on the initial stock of minerals within the ore deposit (Geoscience Australia 2015). Therefore, royalties do not provide incentives to enhance recovery and minimise waste.

This disconnection between the natural resource and the mine's profit is visible in multifactor productivity (MFP) calculations, which include all capital and labour expenditures, but do not include the mineral resource. According to Topp et al. (2008), this may explain the observed decrease in the Australian mining industry's MFP since the year 2000. Mineral resources are becoming increasingly difficult to access and extract, which results in higher expenditures for the same amount of output, hence a decreased MFP. If this change in the quality of the mineral resource (called by Topp et al. the depletion effect) were to be included in MFP calculations, then MFP would be increasing instead, showing that mining companies are making technical and organisational progress, while facing a harsher environment.

In addition, and partly as a result of this lack of economic incentive to minimise waste, waste reprocessing is often not part of most mining companies' core business, which have developed their expertise in mining ore bodies. Therefore, they may be reluctant to explore these opportunities.

Governments on the other hand are – or at least should be - more concerned with the long-term accessibility of the national resources than corporations. Additionally, provincial or national governments become responsible for the legacies of abandoned mine sites.

Because of this, chapter 7 is dedicated to studying the external policy incentives that can facilitate a desirable change in mining practices. Chapter 7 initially reviews previous findings from the literature to examine the role of governments in the management of national mineral resources, and how this translates at the mine site level. It then focuses on the two case studies, by providing background information on existing policy frameworks at both national and state (Tasmania and Queensland) levels and by observing the actual government involvement in Mount Morgan and Mount Lyell, and its influence on mining practices. This analysis offers recommendations for improvements in the future. The last part of Chapter 7 draws on these findings to propose avenues for potential reforms of mining policies in Australia.

4.5. Fieldwork and data collection

The data collection for the three levels of analysis described in the previous section was organised through a common process. It followed a similar approach for both case studies. Because both sites' history have been extensively documented, the first step was to review the readily available documentation and collect as much data as possible from written sources. From this review, a list of missing information, or information requiring clarification, was made.

A second step was to prepare a list of questions related to quantitative data needed for the MFA calculations (i.e. level 1 of the analysis). These questions were sent by email to the main contact person for the case study (Russell Dann for Mount Morgan, Geoff Cordery for Mount Lyell) who were able to provide an answer for each of them.

The third step was to prepare a second list of questions to be asked during the field work. For the interviews that occurred during the field work, a semi-structured approach was chosen. The rational was that a semi-structured and somewhat informal conversation would allow uncovering aspects that may not have been uncovered through more formal interviews.

A first category of questions was dedicated to qualitative historical elements, and was organised around the main periods of the mine's life cycle (i.e. level 2 of the investigation): mining projects and periods of interruption between mining projects. Questions were prepared based on gaps in the documentation and elements requiring clarification. These questions were directed, for Mount Lyell, at Geoff Cordery, who had been present in Mount Lyell during the last years of the Mount Lyell Mining and Railway Company (MLMRC) up to the present time as environmental manager of Copper Mines of Tasmania (CMT). He therefore witnessed the transition from MLMRC to CMT. For Mount Morgan, questions regarding Carbine Resources' project were asked to Carbine's Managing Director Patrick Walta; while questions regarding previous projects were directed to Dr Ray Boyle, former engineer at Mount Morgan Limited, and who dedicated a PhD thesis to the history of Mount Morgan. The interview with Dr Ray Boyle was scheduled thanks to the help of Russell Dann. Additional information was also gathered during informal discussions with Geoff Cordery and Russell Dann during the site visits. When possible, conversations were recorded.

Finally, a second category of questions was prepared in order to investigate the role of the governments in the mines' lives (i.e. level 3 of the analysis). These questions were directed to both company and government representatives in order to obtain both perspectives. The selected government interviewees were directly involved with the two mine sites and were part of the two relevant governmental agencies: mineral resource development (the Department for Natural Resources and Mining in Queensland, and Mineral Resources Tasmania in Tasmania) and environmental protection (the Department of Environment and Heritage Protection in Queensland, and the Environment Protection Authority in Tasmania). When possible, conversations were recorded.

The interviews organised during the field work were also the opportunity to request additional documentation, which was later provided in follow up emails.

Wherever possible, Information about the case studies presented in Chapters 5, 6 and 7 is supported by existing documentation. In the case where a piece of information originates from a specific interview and no written document was found to support it, a reference was made to the personal communication with the interviewee.

4.6. Conclusion

The methodology presented in this chapter aims at expanding the investigation, which started at the mine waste management level in Chapter 3, to three wider levels encompassing each other and the mine waste management level, allowing for a holistic perspective. These three levels are: the mining project, the mine's life cycle, and the policy and regulatory level. Each of these levels are applied – in the next chapters - to the two case study mine sites, Mount Morgan, a gold mine in Queensland, and Mount Lyell, a copper mine in Tasmania.

For the first level, the mining project, a set of 13 Material Flow Accounting (MFA) indicators has been developed in order to model the flows of mineralised material occurring during the mining project and remaining within the mine site boundaries. These MFA indicators quantify the movements of bulk material as well as their mineral content, and help better understand the internal metabolism of a mining project. In particular, different types of mineral losses are located, quantified, and can be weighed against production figures.

The second level makes the distinction between the mining project and the entire mine's life cycle. Both Mount Morgan and Mount Lyell have hosted more than one mining project throughout their lifetime, and a particular distinction between these two levels includes the transition periods from one project to another, as well as the question of the final closure, i.e. whether any future use of the remaining material can be anticipated or not.

For a comprehensive mine life cycle perspective, a qualitative investigation should be performed. It should comprise a retrospective investigation of case study mines' history, to review the consequences of interruptions and ownership changes throughout the mine's life cycle, and a forward-looking SWOT analysis, aimed at identifying barriers and enablers for prolonging operations to enhance mineral recovery and environmental performance.

Finally, the third level of this methodology estimates the opportunities for external incentives to help generate desirable changes in mining practices. A main actor identified is the government, which, as owner of the resource, has a determining role in the context of this thesis, both at the mine project level and the overall mine's life cycle. For this level, findings of governmental intervention in Mount Morgan and Mount Lyell are analysed to formulate conclusions on how mining legislation can evolve in order to encourage the necessary changes identified in the previous steps of this methodology.

Chapter 5 (on Mount Morgan) and 6 (on Mount Lyell) are focused on the mine project and mine life cycle levels, with the application of the MFA indicators to both case studies followed by a holistic view of the two mine's life cycle. Chapter 7 is focused on the governmental role.

5. Case study 1 – Mount Morgan, Queensland

This chapter contains the results of the first case study of this research: the Mount Morgan gold mine in Queensland, Australia. Data collection for this case study occurred during a visit of Mount Morgan and Rockhampton in January 2016. This included the site visit, as well as the interviewing of selected stakeholders representing Carbine Resources, Mount Morgan Limited, and the Queensland Government. A number of publications were also shared prior to the visit.

This chapter starts with a brief history of the case study site. The application of Material Flow Accounting (MFA) indicators to each of the site's mining projects is then discussed. The third part is the qualitative investigation, which comprises a retrospective discussion on the factors and practices that lead to mineral losses, as well as a SWOT-like forward-looking discussion on the barriers and enablers to prolong sustainably the life of the mine.

This chapter was the subject of a publication in the Journal of Industrial Ecology (Lèbre, Corder & Golev 2017), and content from this paper has been used in this chapter.

5.1. Mount Morgan's life cycle

The history of the Mount Morgan mine in Queensland, Australia, is characterised by two past mining projects, as well as one potential future mining project. The second mining project that occurred in the 1980s was reprocessing mine waste, and similar to the new project. It is therefore an appropriate case study to observe the differences between the two scenarios and the influence of waste reprocessing projects on the site's environmental footprint as well as their contribution to mineral recovery. In addition, significant data are publically available due to a number of studies performed during the mine's abandonment period, which produced publications quantifying the extent of the site's environmental legacies. Figure 5.1 shows a satellite view of the site with the positioning of main waste deposits (including pit waste water). Over the life of Mount Morgan, most of the AMD produced within these waste deposits have reached the Dee River situated downstream.

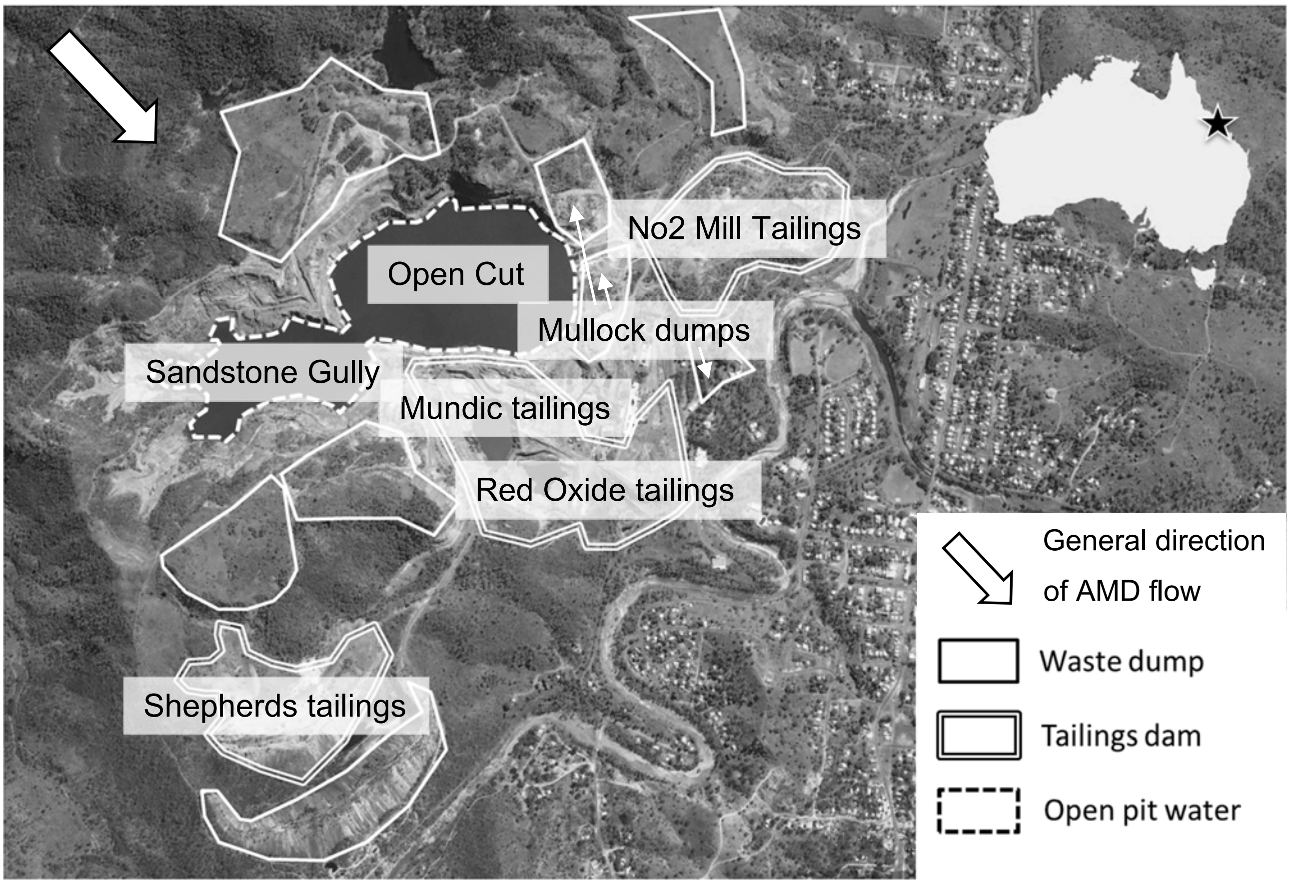

Figure 5.1: The Mount Morgan mine site, 2017, including localization of waste deposits (adapted from Google Earth and Carbine Resources pre-feasibility study (Findlay 2015)). Extracted from Lebre, Corder and Golev 2017

5.1.1. Historical operations (1882-1982)

The Mount Morgan mine in central Queensland, Australia, presents a remarkably long history. It opened in 1882 and extracted gold as the main commodity, and copper and silver as by-products, for over a hundred years with only one temporary interruption between 1927 and 1932. It started as several underground workings, but extended to a large open cut in 1932. The main companies on site were the Mount Morgan Gold Mining Company, from 1886 to 1929, and Mount Morgan Limited, from 1929 to 1982, which became a subsidiary of Peko Wallsend Limited in 1968. Technologies evolved significantly during the mine's life, and successive concentration plants were built including improvements to the froth flotation method in order to process more efficiently sulphide ore, while oxidised ore was processed with cyanide. By the end of the historical operations, 99 per cent of the ore body had been mined (Boyle, RF, White & Wilson 1993).

In the first half of its life, proper containment of tailings and other reactive waste was by today's standards poorly done, and the waste management practices involved the dumping of tailings in the nearby river (Boyle, RF & Gistitin 1992). These practices explain why the mass of processing output, which is dominated by around 40Mt of tailings, is less than the mass of processing input, i.e. 50Mt of ore (see Table 5.1).

However, during the second half of the operations, Mount Morgan Limited started undertaking pollution control measures as well as a rehabilitation program, which resulted in the coverage of around 35% of the waste material (Boyle and Gistitin 1992). Mount Morgan Limited also installed a seepage interception system (SIS), which is still currently in use and able to collect 80% of the AMD and pump it back to the open pit (Wels, Findlater & McCombe 2006). Figures regarding the mine's production and waste generation can be found in Table 5.1.

Despite these efforts, damage to the environment was considerable. Wels, Findlater and McCombe (2006) evaluated that the acidic seepage discharging from the waste deposits impacted heavily on the ground water as well as the nearby river, where fish kills have been observed for 40km downstream of the mine (McCombe 2009). Wels et al. (2006) assume that, because there was no segregation, all waste rock deposits were likely to be acid generating.

5.1.2. Sandstone Gully Tailings Reprocessing (STR) project (1982-1990)

Shortly after the end of ore production in Mount Morgan in 1982, and still under the name of Mount Morgan Limited, a tailings reprocessing project was initiated by Peko Wallsend Limited and extended the life of the mine for another 8 years. The project aimed at extracting gold and silver from sulphidic tailings previously dumped in the Sandstone Gully pit, using a newly built Carbon-in Pulp cyanide plant (Wels et al. 2006). A total of five different companies took over the operations during that time (Boyle and Gistitin 1992).

The operations ended prematurely when gold prices dropped and the company was experiencing technical difficulties. Indeed, the copper present in the tailings reacted with cyanide, the main reagent used for gold extraction, and caused an over consumption of cyanide as well as decreased gold recovery (Carbine Resources 2017). Overall, 28 million tonnes of tailings were reprocessed, instead of the 32 million tonnes initially targeted (Boyle, RF, White & Wilson 1993).

In the end, the deposition of the new tailings in the Open Cut pit generated further environmental damage, which can be attributed to poor environmental practices (Boyle and Gistitin 1992). The rehabilitation program started during the previous operations was abandoned in 1982 and no more remediation measures were undertaken.

Figures for the STR project are gathered in Table 5.1. The extraction did not require any waste rock removal, as the tailings that were being treated were readily available. Besides, the operations took place on already impacted area therefore no additional land was impacted.

5.1.3. Carbine Resources' project

When the tailings reprocessing project closed in 1990, the mine was left abandoned and the entire environmental liabilities were taken over by the State of Queensland. Wels et al. (2006) estimate that since then, every year a minimum of 94 ML of acid and metal bearing water escapes from the waste deposits and reaches the nearby river, its metal content being therefore irreversibly lost.

Unable to perform the expensive long-term rehabilitation program and yet having to cover significant yearly costs for pollution control, the state Department for Natural Resources and Mining (DNRM) actively encouraged collaboration with a new mining company.

The latest proposal is from Carbine Resources, who completed a pre-feasibility study in late 2016. They estimated that a minimum of 8 Mt of tailings and waste rock would be suitable for economic recovery of gold, copper sulphate and pyrite, using a process flow sheet involving two different stages of cyanide leaching, resin-in-leach for copper extraction and carbon-in-leach for gold extraction, as well as a flotation stage for pyrite (Findlay 2015). Copper sulphate can be used in a variety of domestic applications, notably as reagent in the mining industry, in the preservation of timber or in agriculture (Butterworth 2016). The pyrite concentrate extracted would contain about 50% of sulphur from which sulphuric acid may be produced and used mostly for agricultural applications (Carbine Resources 2015).

Material deposits to be processed by Carbine Resources are presented in Figure 5.1. Carbine plans to remove the three main sources of acid mine drainage: Mundic tailings, Shepherds tailings and No2 Mill tailings, as well as the water flowing through these deposits and originating from Sandstone Gully and the Open Cut (Wels, Findlater & McCombe 2006). Additionally, other waste material (tailings, slag or waste rock) present on site could potentially be considered for reprocessing in the future.

Carbine Resources' project represents an opportunity to address the site's environmental legacies. Pyrite would be extracted with high recovery rates (around 90%), which would make the remaining tailings significantly less reactive. Indeed, pyrite is the main mineral responsible for acidic seepage (Dold 2010). Contaminated water from Sandstone Gully and the Open Cut would be used as process water, thereby decreasing the acidic seepage from the pits.

With the Department for Natural Resources and Mines engaging Carbine Resources in the rehabilitation efforts it is to be anticipated that the end of Carbine's project will coincide with the end of the mine's life (Dann 2016). If the project is successful in extracting a significant part of the pyrite on site, this would assist in solving the most critical environmental impact and allow for a proper closure of the mine.

Table 5.1 summarizes the proposed production figures for all three projects. It should be noted that these figures represent a minimum amount and that Carbine's project could potentially extract significantly more, as the 8Mt of tailings are less than 30% of identified gold mineralization on the site (Carbine Resources Limited 2015). Interestingly, the operations (mostly because of the extraction of pyrite) would result in a reduction of the total amount of tailings on site. Existing waste rock would be moved in order to access the tailings to be treated but no new waste rock would be generated.

Table 5.1: Production figures for all three projects: historical operations, STR project and Carbine Resources' development project (Findlay 2015; MMPAD 2014; Boyle and Gistitin 1992; Wels et al. 2006). Extracted from Lèbre, Corder and Golev (2017a)

	Historical operations 1882-1982	STR Project 1982-1990	Carbine Resources*
Main commodity	Gold	Gold	Gold
Type of mining	Underground then Surface	Surface	Surface
Material to be processed	50,000,000 t of ore	28,000,000 t of tailings	8,000,000 t of tailings
Production	Copper: 400,000 t Gold: 225 t Silver: 50 t	Gold: 14 t Silver: 4.5 t	Gold: 9 t Pyrite concentrate: 2,000,000 t Copper sulphate: 40,000 t
Waste Rock Generation	90,000,000 t	~0 t	6,600,000 t
Net Waste Rock Generation	90,000,000 t	~0 t	~0 t
Tailings Generation	40,000,000 t	28,000,000 t	6,000,000 t
Net Tailings Generation	40,000,000 t	~0 t	- 2,000,000 t
New Area Impacted	270 ha	~0 ha	~0 ha

*****Carbine Resources project is expected to have a minimum life time of 8 years based on JORC resources only (Carbine Resources 2015). No start date is determined yet.

5.1.4. Observations across the life of Mount Morgan mine

Over the life of Mount Morgan mine, certain practices have contributed to the exacerbation of mineral losses. Some of these losses may be irreversible, while others are potentially recoverable if appropriate mining and mineral processing technologies become available and are applied as part of a cost-efficient extractive strategy. Typically, AMD losses that have spread out from the mine's boundaries are irreversible, and so are losses of minerals contained in the waste that was dumped in the river during the early days of the mine. On the other hand, AMD losses that were collected by the seepage interception system, as well as minerals locked in waste material on site, may be recoverable in the future (although the questions of how far into the future this recovery could occur, and whether the associated costs and impacts justify the outcome, would need to be addressed).

For the case of Mount Morgan, apart from uncollected AMD losses and the early waste dumping, most mineral losses are still contained within the site's boundaries and therefore potentially recoverable. However, past practices that resulted in diluting, spreading or restricting access to remaining minerals contributed to making a future recovery more challenging and costly.

In the history of Mount Morgan, the premature closure of the STR project was an unfortunate event. It left the mine abandoned, without any source of revenue to mitigate the considerable environmental legacy from about 110 years of operations, as well as leaving significant amount of valuable minerals contained in various waste material.

The transition between the historical operations and the STR project happened while Peko Wallsend Limited was still the mine's owner, which resulted in a smooth transition with no interruption. During that transition and for about two years after, the smelter continued to operate as Peko was bringing in concentrate from another of its mines (Warrego Mine, Northern Territory). However, later on, the succession of several mine owners with diverging interests compromised the project's economic stability and explains the lack of long-term forecasting. These changes in ownership meant that the DNRM could not hold the last owners responsible for past environmental legacies. When the following premature closure occurred, the agreement signed by the DNRM and Mount Morgan Limited, released the company from all obligation, except for completing the decommissioning plan for its own operations, and providing a sum of AU$ 335,000 for the government's future activities on site.

However, most of the environmental damage and mineral losses (see 5.2) occurred before the STR project. The state of Mount Morgan is attributed mostly to the historical operations, whose practices (e.g. the absence of containment of reactive waste, or the initial waste dumping) were allowed at the time as environmental regulations were not as strict as they are today. Forecasting a potential future use for the waste material was deemed unnecessary as long as the ore body was readily extractable.

Today, the potential mineral recovery from waste by companies such as Carbine Resources is possible due to the inefficiencies of previous extractive strategies. However, some of these inefficiencies may have been avoidable. As gold is such a highly valuable product, the recovery of sulphide minerals, which are of lesser value but greater environmental significance for the site, were not considered. The STR project focused on gold production, leaving copper (and pyrite) resources behind. As a result, the economic recovery of remaining copper in the reprocessed tailings is now significantly more challenging than if it were to be extracted as a by-product of gold.

Finally, it is worth noting that there are two mechanisms that contribute to controlling AMD losses while indirectly increasing mineral concentrations in the open cut: the seepage interception system installed by Mount Morgan Limited, and the water treatment plant commissioned by the Queensland Government, which aims at treating the open cut water before it discharges into the local river. These two systems pump back both the collected leachate and the metal-rich sludge to the open cut. Adding them to the various waste materials that were deposited in the open cut during both the historical operations and the STR project, makes it challenging to estimate the resource currently contained within the open cut.

Table 5.2 summarises identified practices that either prevented or facilitated further resource recovery from remaining material.

Table 5.2: Practices influencing mineral losses and their recoverability in Mount Morgan

	Historical operations	STR project
Factors contributing to irreversible mineral losses	- Absence of containment of waste and insufficient rehabilitation: AMD - Inefficiencies in extractive strategy: material more susceptible to AMD	- Poor containment and placement of reactive waste on main AMD route (in the open cut) - Inefficiencies in extractive strategy
Factors preventing future recovery	- Absence of segregation of waste: dilution	- Premature closure, site abandonment - Inefficiencies in extractive strategy

Factors facilitating future recovery	- Absence of containment of waste and insufficient rehabilitation: material readily accessible - Presence of old waste deposits from periods of less efficient extraction - Seepage interception system accumulating AMD in open cut	

5.2. Results of MFA calculations

5.2.1. MFA results for the three mining projects

MFA indicators were calculated for each of the three mining projects at Mt Morgan (see Table 5.3). The Total Production, Total Material Processed and Total Material Moved indicators are presented with their annual average to make the three projects' sizes easily comparable. Details on MFA calculations can be found in Appendix I.

The fixed prices used to calculate the production indicators are the same for all three projects, and are extracted from Carbine Resources' long-term metal pricing forecast (Carbine Resources 2015). This eliminates time dependency of prices and allows for comparison between projects, as discussed in 4.2.

Some of the data necessary for the MFA calculations are missing, especially for the calculation of mineral losses (Mineral Losses to New Waste and Total Mineral Losses to Waste), and consequently for the related Extraction Inefficiency indicator. This was due to the fact that waste deposits in Mount Morgan are old, and no record of their origins or composition was kept. Recovery rates from historical operations were also unknown, which prevented a top-down approach. As a result, Mineral Losses to New Waste were calculated using Carbine Resources' characterization of waste deposits and completed with additional historical data. However, Carbine Resources' exploration target covered only 34% of all waste material on site, hence the historical operations' mineral losses to waste and the related indicators are likely to be underestimated.

This may affect the MFA results for historical operations and lower their performance relative to the two other projects: Mineral Losses to New Waste, Total Mineral Losses to

Waste and Extraction Inefficiency would be higher. However, this is unlikely to change the overall conclusions of the study, as MLNW and TMLW are already the highest for the historical operations, and if they were to double, the historical operations' EI would rise to 45% and thus remain between those of the STR and Carbine projects (see Table 5.3).

Carbine Resources' exploration did not report on silver, as the company did not intend to recover this metal, nor were pyrite concentrations available, except for a rough estimation from Wels, Findlater and McCombe (2006), who stated that material on site could carry up to 10% of sulphur content. Pyrite losses to waste for both historical operations and the STR project were therefore determined with high uncertainty levels, using Carbine's expected production and recovery rates, deducing concentration the waste material processed, and assuming homogenous concentrations for all waste material on site.

Table 5.3: Values of MFA indicators for each mining project.

	Historical operations	STR Project	Carbine Resources
Years of operation*	100	8	8
Total Production TP (M$)**	10,200	510	520
Annual Production AP (M$/year)	102	64	65
Total Production from Waste TPW (M$)	0	510	520
Total Material Processed TMP (Mt)	50	28	8
Material Processed Annually MPA (Mt/yr)	0.5	3.5	1
Total Material Moved TMM (Mt)	140	28	14.6
Material Moved Annually MMA (Mt/yr)	1.4	3.5	1.8
Net Waste Generation NWG (Mt)	130	0	-2
Material Efficiency ME ($/t)	73	18	35
Mineral Losses to New Waste MLNW (M$)	4,300	1,100	140
Total Mineral Losses to Waste TMLW (M$)	4,300	590	-380
Extraction Inefficiency EI	30%	68%	21%
New Area Impacted NAI (Ha)	270	0	0

** Colours are used to visualise the performance of each project relative to a particular indicator and compared with the other two projects. A negative performance is highlighted in orange, a positive performance in green, and a neutral performance remains uncoloured.*

*** The monetary unit used for all MFA calculations is US$.*

The STR project and Carbine Resources' project both show some advantages compared to the historical operations, which are due to the fact that they are both reprocessing waste on an already impacted site. The New Area Impacted is null, and Net Waste Generation is either null for the STR project or negative for Carbine, which means that Carbine would be recovering more value than it is losing it in the waste stream. The Total Material Processed, Total Material Moved, Mineral Losses to New Waste and Total Mineral Losses to Waste are also significantly lower compared to the historical operations. This should however be mostly attributed to the longevity of the historical operations.

Significant differences in Total Material Processed, Total Material Moved, Mineral Losses to New Waste and Total Mineral Losses to Waste are however visible between the two waste-reprocessing projects, which are similar in production size and longevity. The results show that the STR project does not do as well as Carbine for most indicators. It has the highest rate of material moved and material processed annually, and its MLNW is ten times higher than Carbine's. It also has the lowest Material Efficiency and the highest Extraction Inefficiency of all three projects. The high EI and MLNW are due to a low gold recovery rate (50% compared to 76% for Carbine resources, see Appendix I) and the absence of copper and pyrite recovery. The low ME is due to a larger amount of material moved for a production similar in value to Carbine's forecasts. The historical operations show the highest ME, which is probably favoured by high ore grades, as well as its exceptionally long lifetime, which enhanced production against initial waste rock material displacement. However, its mineral losses are high, and underestimated: it is likely that including minerals contained in unexplored waste material, as well as waste discharged in the local river would double the historical operation's MLNW.

Carbine Resources' project would perform generally better than the STR project. Although the two projects are similar in their production numbers and lifetime, Carbine's project is predicted to move and process significantly lower annual rates of material, to have a Material Efficiency twice that of the STR project and to have the lowest Extraction Inefficiency of all three projects. This can be explained by Carbine's technical choices and extractive strategy, notably the fact that it recovers three different commodities from waste material, and with high recovery rates.

Therefore, while both reprocessing projects allowed for extending the life of the mine and extracting more value by recovering mineral losses of the past, they exhibit significant differences. Adding to the drawbacks of the STR project's premature closure, MFA results for the STR project show that reprocessing of mining waste is not a sufficient condition to guarantee desirable environmental and economic outcomes. In particular, the project's high EI, low ME, and small production value indicate an inefficient extractive process.

Overall, the two waste reprocessing projects combined would recover around US$ 1,000 million worth of gold, copper and pyrite, out of a stock of at least US$ 4,300 million (but potentially significantly larger) previously wasted during the historical operations, i.e. about 23%. It is worth connecting this result with the scenarios presented in section 4.1.1, as the MFA indicators development aimed at providing insight into these theoretical scenarios. The actual life of Mount Morgan and its three mining projects correspond to scenario B, i.e. the re-mining and reprocessing scenario that results in an extended life of mine. Scenario B therefore results in a net improvement in terms of resource recovery compared to scenario A, which corresponds to the Mount Morgan Limited project only.

As a result of this activity, and notably due to pyrite recovery, Carbine Resources' project contributes to removing some of the reactive material located upstream of the Dee River, hence reducing AMD and the related contamination of the local river system. Whether this is enough to significantly improve the ecological state of this system is another question, which would require a separate and more detailed analysis. With the current pre-feasibility study, Carbine would still leave the majority of the reactive material behind, although this is only a base case scenario and the life of Carbine's project could be extended.

Scenario B's environmental footprint may not represent a significant improvement compared to scenario A. The two reprocessing projects do contribute to a marginal increase in the mine's environmental footprint, while at the same time increasing resource recovery. The question would then be whether scenario B contributes to an increase in eco-efficiency, i.e. the production over environmental impact ratio (P/E). For the Material Efficiency indicator, which can provide a partial representation of the P/E ratio, scenario B would in fact result in a decrease in material efficiency from 73 in scenario A to 61. This is because Carbine and STR projects' ME is lower than the historical operations' ME. However, for a P/E ratio to be complete, one would need to take into account several other environmental indicators, such as Net Area Impacted, or the pollution generated by acid mine drainage. It is possible that scenario B's overall production over impact (P/E) ratio would be slightly higher than scenario A. However, many other factors would need to be included in the environmental footprint to obtain a reasonable estimate of the eco-efficiency.

5.2.2. Estimation of Irreversible Mineral Losses through Acid Mine Drainage

Regarding the IML-AMD indicator, only an order of magnitude could be estimated. The result is not presented in Table 5.3 as it was not possible from the available data to calculate the values of IML-AMD for each project. Pollution from AMD in Mount Morgan is documented, in particular by Wels, Findlater and McCombe (2006) who developed an underground water model. However, Wels, Findlater and McCombe estimate the volume of AMD water leaving the mine site, but do not provide an average chemical composition of that water. As a substitute, the results of open pit water samples performed in 2014 (LPSDP 2015) were used to approximate the AMD water average composition. According to Wels, Findlater and McCombe (2006) the majority of seepage originates from the open pits. However, by following the general flow direction shown in Figure 5.1, AMD then leaves the open pits and continues to flow through the waste deposits downstream, while the rest seeps directly into ground water. Overall, AMD water comes in contact with various reactive material before reaching the river or the ground water, and is likely to have higher concentrations of dissolved minerals than the water in the pit, hence IML-AMD is probably underestimated.

Using this approximate data, it was estimated that about US$1.5 million were lost in AMD over a 20-year period (assuming steady-state occurred a few years after the mine was abandoned). This means about US$2 million were lost between the closure of the STR project and the expected start of the Carbine Resources project. This aggregated value includes copper and sulphur (converted in pyrite concentrate equivalent), however it excludes gold and silver, whose concentrations in AMD waters were not reported. Nevertheless, Carbine's production excluding gold revenues is estimated to account for about US$190 million. Although the estimated amount lost in AMD between the two projects is not insignificant, it is however small compared to the total resource remaining on site.

Estimation of Irreversible Mineral Losses through AMD, although likely to be underestimated, shows that AMD is overall a slow process compared to mining activities, whose yearly productions (AP) may be two to three orders of magnitude higher than yearly AMD generation. It means that although AMD flows are highly important in terms of the mine's environmental impacts and legacy, the mineral losses due to AMD are not significant and should not have a strong effect on mining revenues.

5.2.3. Conclusion on MFA results for Mount Morgan

Applying the MFA indicators to the three mining projects in Mount Morgan has allowed for quantifying some key characteristics of the projects' metabolisms. Firstly, it quantifies mineral losses that occurred due to the inefficiencies of extraction (Mineral Losses to New Waste and Total Mineral Losses to Waste). Mineral losses could be compared to production figures of the related project as well as those of future projects. The production numbers for the two reprocessing projects showed a potential to recover a significant fraction of previous losses.

The MFA indicators also allowed for characterising the efficiency of extraction relative to both mineral losses (Extraction Inefficiency) and the movements of bulk material required for production (Material Efficiency). Other bulk material indicators expressed in tonnes provided information on the material intensity of mining activities, linking monetary values to a physical flow (Total Material Moved, Total Material Processed, and Net Waste Generation). These indicators, as well as New Area Impacted expressed in hectares, also provided information on the extent of the environmental disturbance caused by mining activities.

Overall, the MFA results show that the three mining projects differ significantly in their performance, notably in their ability to recover lost minerals and prevent new losses, which originates from different extractive strategies. Results for the STR project show that the project's new mineral losses are higher than its production, which suggests a poor performance compared to Carbine Resources. The results for Carbine showed that, under the right conditions and with the help of recent technological progress, a reprocessing project should have a positive impact on the local environmental footprint of a legacy site such as Mount Morgan.

5.3. The future of Mount Morgan

The current situation in Mount Morgan suggest that the mine has a future. Carbine Resources is currently the most likely - if not the only - option for the future of Mount Morgan, and although the available information on the project is promising, it is still unknown how it will eventually perform. The MFA indicators are only providing an estimate of Carbine’s performance given current state of knowledge, and there are other available pieces of information that can provide some insights into the mine’s future.

Therefore, to supplement and support the results of the MFA indicators, a qualitative analysis, using the Strengths, Weaknesses, Opportunities and Threats (SWOT) framework, was conducted to explore the internal and external factors that are either favourable or unfavourable for the Carbine Resources project to be successful. The meaning of successful is that the project would not only be economically viable (a prerequisite), but also have a significant positive impact on the environmental state of the Mount Morgan mine. Setting as an objective that Carbine’s project should enable a complete rehabilitation of the site would be unrealistic, because of the small size of the project compared to the extent of the environmental legacies. However, it can potentially make a significant contribution.

5.3.1. Internal factors: strengths and weaknesses

One of the main strengths of Carbine Resources’ project is technological. The technological expertise of Carbine allows them to generate three products, hence three revenue streams. Besides, these three separate revenue streams are relatively balanced: Carbine estimates approximately US$320 million revenue from gold, US$120 million for pyrite and US$70 million from copper sulphate. A diversified production may contribute to making the project’s economic viability less sensitive to fluctuations in commodity prices. On the other hand, a shortcoming of Carbine’s process flow sheet is the absence of silver recovery compared to the two past mining projects.

The designed process flow sheet is also characterised by improved recovery rates compared to the previous STR project, and a low reagent consumption, which contributes to decreasing the cost of operations (Carbine Resources 2015). Because of this improvement, Carbine’s overall production value (TP) is similar to that of the STR project, while it is moving (TMM) and processing (TMP) significantly less material in tonnage.

Contributing to a low cost of operations is the limited need for grinding. The material to be re-processed is already finely grained, and the oversized fraction (10%) will be eliminated in an initial processing stage by a trammel (Findlay 2015). Grinding is often the most energy intensive stage of mineral processing (Wills & Napier-Munn 2006), hence a significant amount of energy can be saved compared to more traditional mining operations. On the other hand, this also means that all oversized material on site will be most likely excluded from future plans, which may exclude a significant portion of waste rock. Another factor in favour of reduced energy and other resource requirements is the limited mining stage, as tailings are above the surface and can be excavated without much overburden to remove. This also contributes to a low Total Material Moved for Carbine.

Carbine’s technological strength may also be a weakness, as processing facilities are complex and expensive, and the complicated flowsheet requires a detailed interlinked schedule.

In terms of contribution to mine site rehabilitation, the mineral processing flow sheet designed by Carbine for its future operations could potentially reduce AMD generation and partially remediate the site. Carbine would recover US$190 million worth of copper sulphate and pyrite over its life of mine, while approximately US$1.5 million is being lost in AMD over a twenty-year period. The comparison of these numbers suggests that Carbine’s positive impact would be significant, as shown by the Net Waste Generation in the MFA results. According to Wels, Findlater and McCombe (2006), some of the waste deposits targeted by Carbine for reprocessing are also the main sources of AMD (Mundic, Shepherds and No 2 Mill tailings), which suggests that AMD generation would be significantly reduced. Red Oxide tailings, also targeted for reprocessing, are unreactive and do not contribute to AMD.

However, AMD pollution may not be entirely eradicated, as the total amount of copper and pyrite left on site is likely to be in the order of US$1 billion worth, which is much higher than Carbine’s expected production. In terms of tonnage, current mine plans include only the reprocessing of a small portion of the waste material present on site – 8 million tonnes against 130 million tonnes of mineralised waste in total.

Whether Carbine will be successful in remediating significantly the site's environmental legacies will also depend on its activities conducted outside of production. On the waste management side, Carbine states that they will generate benign tailings which will be contained in the open pit and thus prevent some of the AMD generated by water flowing through the open pit. Its general involvement in rehabilitation is however not yet determined, as Carbine is not responsible for past legacies and has therefore no legal obligation.

However, Carbine's business model may allow for a special kind of involvement in the area. Indeed, Carbine Resources is a joint partner of the Raging Bull Group, a group of companies with metallurgical processing and environmental management expertise that specialises in 'economic rehabilitation' through the reprocessing of tailings from historic mine sites (MMG 2017). Another project originating from the Raging Bull Group is starting in parallel with Carbine Resources' project, the Century Mine Rehabilitation Project Pty Ltd at the Century zinc mine in Queensland.

Mount Morgan is Carbine's first project, and as a result it is likely there will be teething troubles, which may also be a weakness. Carbine's business focuses on metallurgy, which means their expertise do not cover the entire life of a mining project and as a result, they need to hire contractors for purposes such as the tailings storage facility design and the exploration phase.

5.3.2. External factors: opportunities and threats

For Carbine to be successful, it needs to take advantage of the site's current state, despite the fact that past owners have not anticipated potential future uses for the site, and seek opportunities from the situation. An example is how contaminated water and different types of solid waste currently occupy the Sandstone Gully pit, which Carbine needs to remove if it plans on building the new Tailings Storage Facility there. However, Carbine would make some revenue from this excavation since the material would be sent to the processing plant.

Some of the existing infrastructure can be reused in Carbine's project, such as the water treatment plant and the seepage interception system (SIS). Having an SIS offers the possibility for some of its discharge to be sent to the process plant, although the contribution to mineral recovery would be small as the estimation of Irreversible Mineral Losses through AMD suggests. This fits well with the need to monitor the SIS and redirect the AMD away from the open pit. Carbine can also operate the water treatment plant for any extra water that does not feed the process plant.

Carbine benefits from past investigations on the site, and makes use of some information for its project. The environmental legacies, although complex, have been well described in several publications (e.g. Boyle, RF & Gistitin 1992; Unger et al. 2003; Wels, Findlater & McCombe 2006). The history of Mount Morgan Limited is well documented and the age of some of the tailings dumps could be estimated. In the recent years, three companies - Perilya Ltd, Moonraker Pty Ltd and Norton Gold Fields Ltd – were previously present on site and performed various studies (Carbine Resources 2017). Perilya explored for ore body extensions and identified an underexplored in-situ resource. Moonraker performed some mineral processing testing. In the early stages of the project's development, Carbine reviewed historical production data and exploration data. Learning from these past studies, Carbine was able to build on them to develop an improved methodology.

Carbine's project is also favoured by a supporting government. Understanding that this company may be Mount Morgan's last chance for low-cost remediation activities, the Queensland government is facilitating Carbine's project to some extent. Negotiations are under way to reduce royalties for Carbine which argues that minerals extracted from waste should follow a different taxation regime than minerals coming from natural ore bodies. Carbine may also get other privileges such as not having to complete an environmental impact assessment. Carbine now owns the entire mining lease, with the native title being extinguished, and no other potentially conflicting party on site.

However, the government stakeholder may also be a source of complications. For example, Mount Morgan is a heritage-listed site, and some of the former protected pieces of Australia's mining history are located in the way of Carbine's activities. The heritage area is the responsibility of the Department of Environment and Heritage Protection (DEHP), and Carbine needs its formal approval for the Project to proceed.

Another more significant complication is the special status of Carbine's business. Standing in between a mining activity and a waste management activity, the company needs to deal with several government agencies that have different and sometimes conflicting interests, and that are not used to projects of this nature. In particular, Carbine Resources' activities are related to both the Mineral Resource Act and the Waste and Recycling Act.

Overall, the government is concerned about setting a precedent and providing a favourable treatment to a company without being certain of the future results (Pegg 2016).

Finally, Mount Morgan is not a remote site, and Carbine's project can benefit from being situated close to a local town, skilled workforce in the region, and the proximity to ports and rails. Being close to both the Rockhampton and Gladstone regions it can also easily find local suppliers and contractors.

The possibility of processing waste material from other nearby mines was explored. However, the potential candidate, Mount Chalmers mine, has relinquished its lease, and no mining activity can therefore take place there anymore.

Using tourism as a way to gain visibility and boost the economy of the local town may be another opportunity for Carbine, which could use the heritage status to its advantage. Universities such as the Central Queensland University and the University of Queensland have had a long-term interest in the site (Boyle, RF & Gistitin 1992) and some collaboration could come from this side as well, if they were to be encouraged by Carbine.

Carbine seems to benefit from enabling external conditions as well as the technological expertise to have a profitable business. However, for it to have a substantial positive effect on the legacies of Mount Morgan, it will need to extend its mine plans significantly further than what the current pre-feasibility forecasts. In particular, production of pyrite concentrate is paramount to address AMD.

The government stakeholder appears critical for the development of Carbine's project. Its support is justified as it has an interest in assisting the new mining project in the hope of addressing mining legacies and creating jobs. However, Carbine's special status may create complications and delays during the approval process, which could severely affect a young company that works on building the trust of its shareholders.

5.4. Conclusion

This chapter presented the case study on Mount Morgan in Queensland. The application of the MFA indicators provided some insights into the performance of the three mining projects in Mount Morgan. In particular, it provided quantitative results related to the projects' production, environmental footprint, and eco-efficiency, and more specifically to the generation and reprocessing of waste material.

The two (past and currently under consideration) waste reprocessing projects at Mount Morgan showed the potential to extract more value and extend the life of a mine while recovering mineral losses. However, the STR Project's inefficient extractive strategy and poor waste management contribute to constraining further resource recovery while not addressing the AMD issue. Carbine Resources' project could potentially leave the site in a better state through generating benign tailings, thus coupling mineral processing with environmental remediation. The results of the MFA indicators show the benefits of mineral recovery from waste, and differentiate both reprocessing projects in the efficiency of their extractive strategy.

The application of the MFA indicators to Mount Morgan thus answer the secondary research question b): "how does such a change in waste management practices improve the overall metabolism of a mine site, and how can this improvement be measured?". The MFA indicator set allowed for estimating the potential improvements (or absence of improvement) that waste reprocessing projects can make, in this case for Mount Morgan.

The results would however benefit from more detailed data, and while using Mount Morgan as a case study provided sufficient publicly available data, the age of the site meant more precise past records were lost. In addition, the indicator set could be improved by adding indicators for external resources use such as water, energy, or chemical reagents consumed in mineral and metallurgical processing. Moreover, they should be used as part of an overall waste management strategy, which also considers downcycling options for remaining waste material, beneficial uses of non-mineralized mining waste and mine land rehabilitation requirements. Mount Morgan did not exhibit any waste downcycling or waste reducing activities, and this case study did not allow visualising the complete Mine Waste Management Hierarchy as presented in Chapter 3.

The SWOT-like discussion complemented the MFA indicators in order to provide some qualitative insights into the future of Mount Morgan. It identified the main drivers and obstacles for the life of Mount Morgan to be prolonged in a successful manner. Combined with the MFA indicators, the approach offers overall a comprehensive view of the mine life cycle, as it assesses past and future practices in their potential for an enhanced resource recovery coupled with environmental mitigation.

6. Case Study 2 – Mount Lyell, Tasmania

This chapter contains the results of the second case study of this research: the Mount Lyell copper mine in Tasmania, Australia. Data collection for this case study occurred during a visit of Queenstown and Hobart in December 2016. This included the site visit itself, as well as the interviewing of selected stakeholders from Copper Mines of Tasmania, the University of Tasmania and the Government of Tasmania. Some data were also shared by email prior to the visit.

Chapter 6 follows a similar structure as chapter 5, with an added comparison between Mount Lyell and Mount Morgan throughout the chapter, and concluding remarks on the usefulness of the MFA indicator set.

6.1. Mount Lyell's life cycle

Like Mount Morgan, Mount Lyell presents a remarkably long history, with the discovery of its first copper deposit, the Iron Blow, dating back to 1883 (SDAC 1995). Because of an exceptionally large mineral resource, mining in Mount Lyell occurred almost continuously between 1888 and 1994, year of its first closure. After an initial settling period, only one company – the Mount Lyell Mining and Railway Company (MLMRC) - remained on site, operating from 1903 to December 1994. One year after this first closure, a second mining project started, operated by Copper Mines of Tasmania (CMT).

6.1.1. Historical operations (1888-1994)

The historical operations in Mount Lyell were one of the largest and most long-lasting operations in Australia, with a mining lease of about 2300 hectares and 120 million tonnes of ore processed during the 106 years of operations (Queenstown Tasmania non dated). Mount Lyell is characterised by a diversity of ore deposits with varying mineralogy, and operations in Mount Lyell consisted of multiple open cuts and underground workings (see Figure 6.1 and Appendix II).

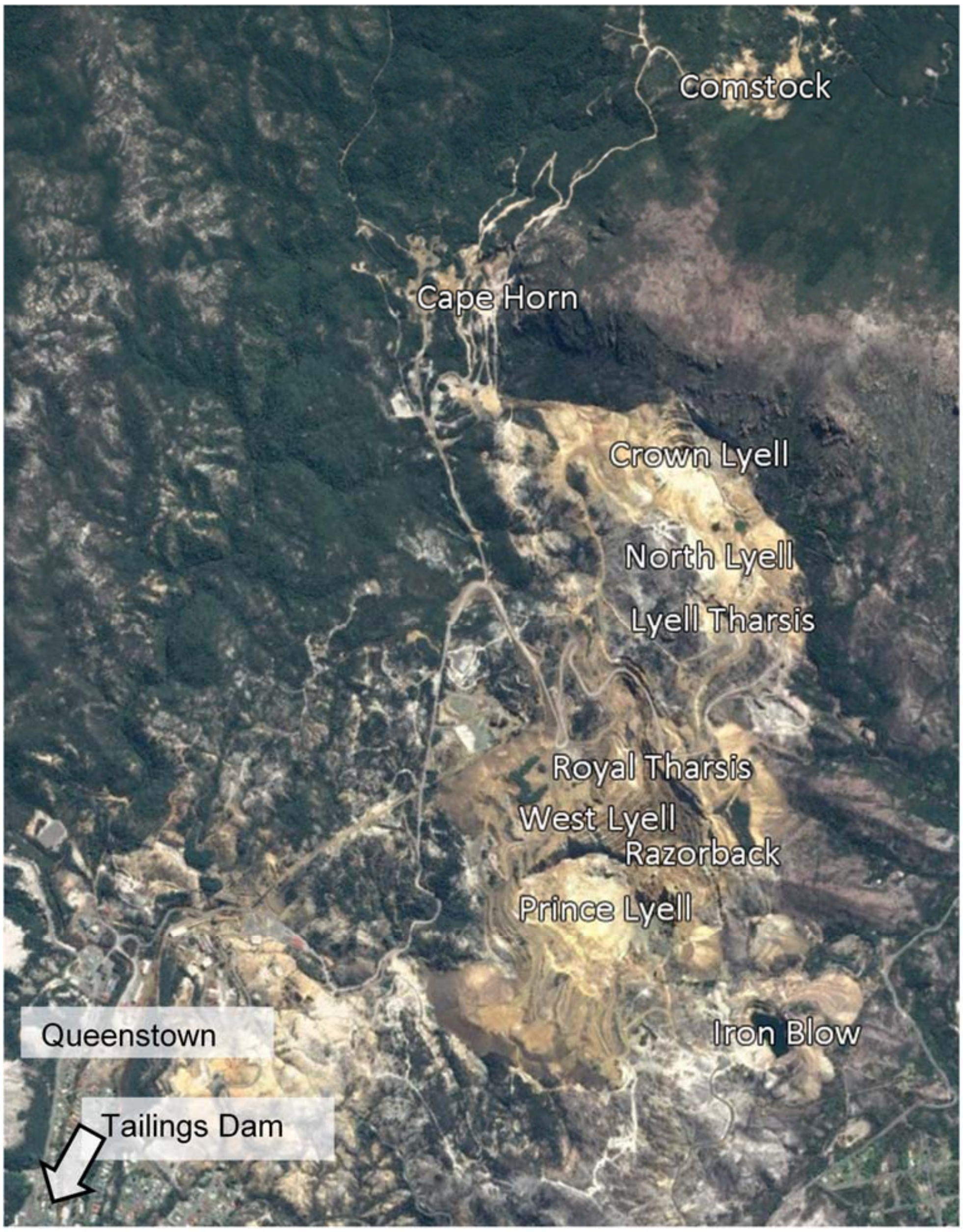

Figure 6.1: The Mount Lyell mine site, 2017, including localization of main open cuts and underground mines (adapted from Google Earth).

Smelting was performed on site until 1969, and until 1922 the crude ore was fed directly to the smelters without a prior concentration phase. During the first three decades of Mount Lyell mine's life, the sulphur fumes caused a drastic change in the local landscape, with tree felling, exacerbated bushfires and soil erosion. The bare hills of Mount Lyell, despite some partial revegetation, are still a tourist feature of the region (SDAC 1995). After 1922, a concentration phase was added using flotation technology. Smelting ended in the 1960s (Koehnken 1997).

Another significant source of environmental damage was the dumping of tailings and slag in the nearby Queen River, which happened consistently until the closure in 1994. 97 Mt of tailings and 1.4 Mt of slag were dumped (Taylor et al. 1996). Most of the waste material was carried away by the river's flow and its contaminants have spread out to the downstream King River, and to the delta, where the King River reaches the Macquarie Harbour. The entire river system, about 100 km long, is in extremely poor ecological health, and Queen River is considered ecologically dead (Cordery 2016).

Waste rock however remains on site. It was deposited in an uncontrolled manner, and with no record of its origins or its composition, and with no AMD prevention measure. Like Mount Morgan, most of the excavated material has high sulphur content and is acid generating. AMD water flows through waste deposits, although the majority of it (78%) comes from underground tunnels (particularly North Lyell and Conveyor tunnels, see Appendix II), where water comes in contact with exposed ore (Koehnken, 1997). Water has always been a critical feature in Mount Lyell, where mean total rainfall is of 2,800 mm per annum (Koehnken, 1997). Water needs to be constantly pumped out of the underground workings to safeguard access to the ore, and during the MLMRC operations it was also discharged in the Queen River.

The closure of 1994 was planned, although no rehabilitation had been undertaken at the time. The MLMRC was required to leave an AU$1.5 million fund to the State Government to be used toward the remediation of the site (Koehnken, 1997). After 1994, the Australian Government took back the ownership of the mining site, including its environmental legacies.

Today, Mount Lyell with the vestiges of MLMRC's operations is a tourist attraction, offering a spectacular view of the Iron Blow pit accessible from the road. Because of its long history, it is a heritage-listed site with numerous old machines and infrastructure, which have been preserved. The surrounding bare hills caused by past smelting activities are a typical feature of the region.

6.1.2. Copper Mines of Tasmania (1995 to present)

Several publications were produced in the 1994-95 period at the request of the Tasmanian government, in an attempt to evaluate both the potential remaining resources and the extent of the environmental legacies in Mount Lyell. The possibility for environmental remediation was explored, however, options investigated were considered too expensive, above AU$10 million in capital costs, adding to this several millions of dollars in annual operating costs (EPA Tasmania 2013).

Around that period, the Tasmanian government undertook some work to divert fresh water from the site and thus reduce AMD generation. However, understanding that the significant amount of resource remaining un-extracted was also a major cause of AMD, the government chose to focus on actively looking for a new operator to continue extraction and prevent the mine from permanent closure.

The proposal from Gold Mines of Australia Ltd was successful, and the Copper Mines of Tasmania mining project started in 1995, producing a copper concentrate using conventional crushing, grinding, flotation and filtration process with the ore mined in Prince Lyell underground. In 1999, CMT was bought by Vedanta, an Indian company, and has continued operating under their direction until now. Most of the infrastructure present on site was reused as part of the new operations, with improvement made to the processing plant, increasing the recovery rates.

CMT was required to operate in accordance with best environmental management practices and build a state-of-the-art tailings storage facility (TSF), 8 km away from the historical mine lease (Cordery & Ritchie 2016). Tailings are treated with lime to remove acidity, thickened and then carried via a pipeline to the TSF, where they are stored underwater, which minimises tailings' reactivity as they are saturated with water.

Similar to Mount Morgan, environmental legacies were declared to not be the responsibility of CMT. CMT agreed to take responsibility for 3% of the AMD originating from the underground workings in which CMT operates, with possible incremental increases of that percentage as CMT progresses deeper underground (Koehnken, 1997).

6.1.3. Recent events

The mine was placed on care and maintenance after three workplace deaths in two incidents in December 2013 and January 2014 (TMEC 2016). These events occurred at a time of low copper prices, and the care and maintenance period was therefore extended

(Australian Mining 2015). About 200 people lost their jobs (Kempton 2014), with only 15 employees remaining in Mount Lyell for care and maintenance coverage. Concerned about the consequences of a permanent closure, the State Government has offered about AU$25 million in payroll tax and royalties, on the condition that the mine reopens (ABC 2015). However, at present CMT has not yet restarted its operations.

Mount Lyell is hence facing again a risk of closure, which would leave behind at least 29 900 000 tonnes of ore according to the Geological Survey of Tasmania (MRT 2017).

Adding to the government's concerns, the AMD problem is still unresolved. Since the beginning of CMT's operations, AMD waters keep flowing from the site to the Queen River, and the State Government continues to seek potential solutions. Options to build a water treatment plant were considered, all of them ultimately deemed uneconomic. Creating revenue from mineral recovery is therefore an attractive and a possibly necessary option.

The Acid Drainage Remediation Act, signed by CMT in 2003, was developed by the State Government and states that the Crown, being the owner of any minerals contained in Mount Lyell's AMD waters, is allowed to assign the rights of extraction of these minerals to a company other than CMT. In 2013, the Tasmanian Government advertised a request for proposals to commercially extract metals from the site's AMD waters (EPA Tasmania 2013). A number of proposals were received, however ultimately none of them were able to prove their operations would be viable without government subsidies, which is a criterion required by the Acid Drainage Remediation Act.

Table 6.1 summarises the main characteristics of the two mining projects in Mount Lyell.

Table 6.1: Production figures for the two projects: Mount Lyell Mining and Railway Company historical operations and Copper Mines of Tasmania

	MLMRC: 1888-1994	CMT: 1995-2012
Main commodity	Copper	Copper
Type of mining	Underground and Surface	Underground
Material processed	120 000 000 t of ore	39 000 000 t of ore
Production	Copper: 1 220 000 t Gold: 33 t Silver: 610 t Pyrite concentrate: 430 000 t*	Copper: 450 000 t Gold: 8.4 t Silver: 641 t
Waste Rock Generation	55 000 000 t	1 000 000 t
Tailings Generation	111 000 000 t	39 000 000 t
Area Impacted	2800 Ha	369 Ha

*For a period of 6 years in the 1980s pyrite concentrate was produced (Newnham 1993).

6.1.4. Observations across the life of Mount Lyell mine

Similar to Mount Morgan, past practices in the areas of waste management and environmental management in Mount Lyell have played an essential role in influencing the extent of mineral losses from the mine. Systematic waste dumping was probably the most significant practice, because of the quantity of material dumped, and the permanent nature of the resulting mineral losses. More generally, waste and environmental management practices happening during MLMRC operations were poor, with a mostly uncontrolled waste disposal, little done in the area of rehabilitation, and no system in place to divert fresh water away from the site (preventing fresh water contamination) or to intercept acidic seepage.

Added to this, MLMRC started to experience financial difficulties in the 1970s (Newnham 1993). As a result, cut-off grade was increased to prioritise the extraction of more valuable material while ignoring lower-grade material, which means that higher amounts of minerals were left behind. Around that time, Commonwealth and State governments provided temporary loans to keep operations going.

The planned closure of MLMRC could have resulted in the loss of significant amounts of resource left behind. Fortunately, the government helped maintain the mine and find a future operator, and the transition from MLMRC to CMT went smoothly. MLMRC cooperated in the search for a new operator, notably by allowing site visits (SDAC 1995). They also provided assistance in the assessment of the mineral resource potential (Newnham 1993), which estimated the Resource Left Behind (RLB) at the time, performed by Newnham Exploration and Mining Services for the Tasmanian Development Authority.

If the government intervention was beneficial in a way that they prevented permanent closure and consequent mineral losses, it did not contribute to finding solutions related to environmental legacies. The agreement with CMT ensured immunity and indemnity for CMT (Thomas 1994), and just like in Mount Morgan, the Crown took responsibility for all past legacies. As a result, and because the government did not have the mean to tackle the AMD issue by itself, AMD generation has kept a steady rate for the past few decades.

Over a twenty-year period, approximately US$79 million worth of dissolved copper and sulphur were lost in AMD. In tonnage, 13 000 tonnes of copper and 190 000 tonnes of sulphur were lost (Koehnken 1997). See Appendix II for details on calculations. Comparing with AMD generated during the same period in Mount Morgan, Mount Lyell generated one order of magnitude more sulphur and two orders of magnitude more copper. Higher concentrations of dissolved copper in AMD can be partly attributed to higher copper grades in Mount Lyell, however this is not sufficient to explain such significant differences. Results for Irreversible Mineral Losses through AMD show that AMD in Mount Lyell is exacerbated by a wet climate, and possibly a larger surface available for the chemical reaction to occur.

Because CMT was declared a project of State Significance for Tasmania, measures were focused on making the CMT project successful economically, while still following best practices in environmental management. However, if mining activities were allowed to continue until most of the reactive and exposed material underground was extracted, AMD generation could potentially be reduced.

Figure 6.2 presents the evolution of average ore grades mined since the beginning of mining activities in Mount Lyell. After an initial rapid decrease, ore grades have been stagnating since the 1940s up to now. The fact that mining operations have been sustained for so long under these relatively stable conditions suggests that they could continue at least until another significant ore grade decline is observed. Recent consistent ore grades support the indication of substantial amounts of ore remaining on site.

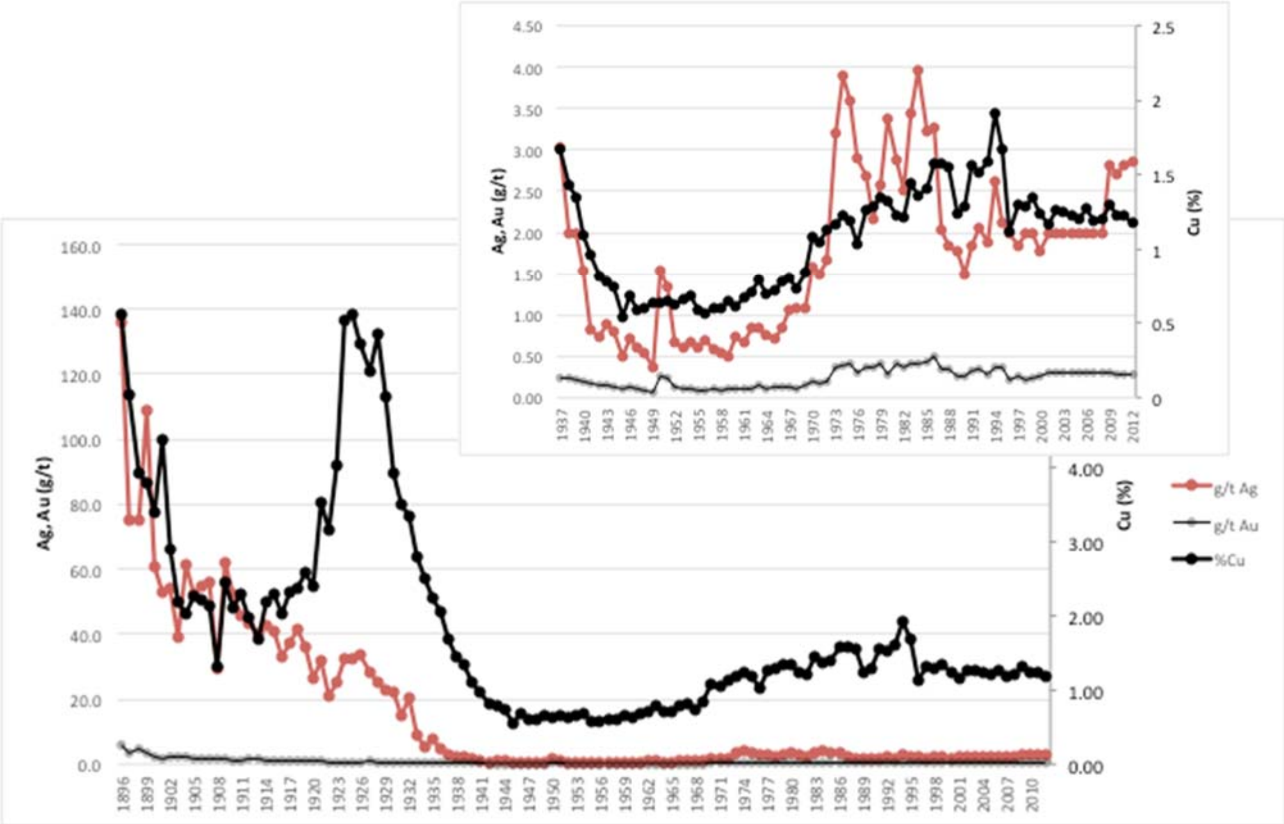

Figure 6.2: Evolution of ore grades throughout Mount Lyell's history. Source: Mudd (2009)

Figure 6.3 shows the evolution of metal production in Mount Lyell since the opening of the mine. The production of copper - the main commodity - has had a consistent upward trend since the beginning of the operations, while gold and silver production remains relatively stable since the 1940s, after an initial decline. The noticeable drop in metal production around the early 1990s coincides with the transition from MLMRC to CMT in 1994.

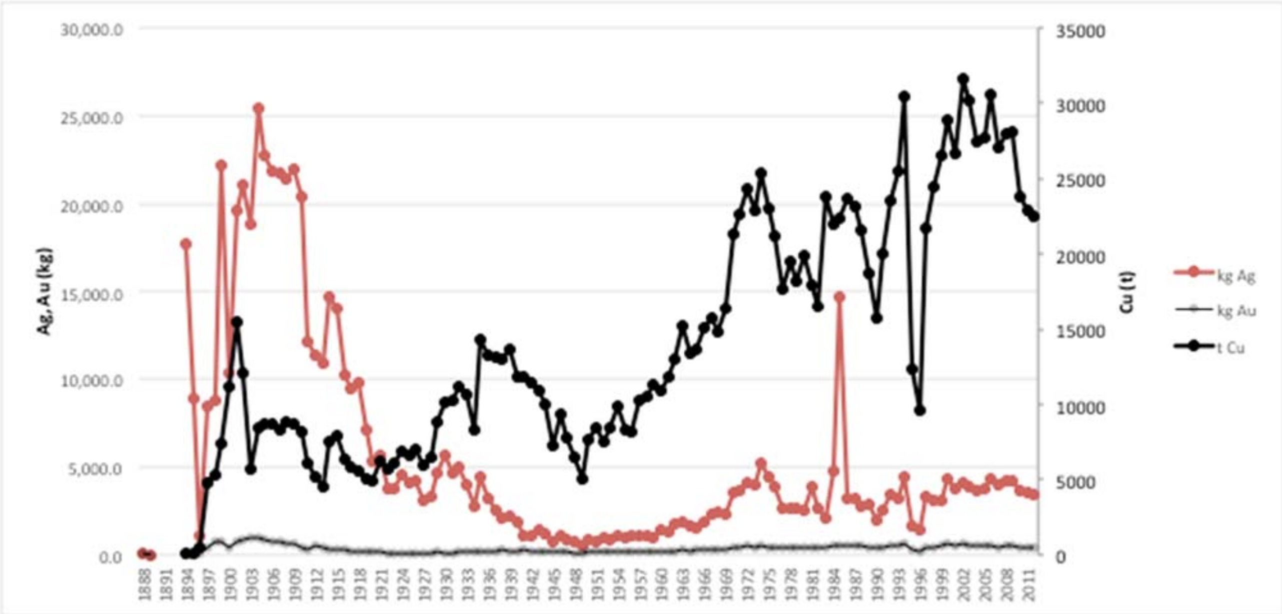

Figure 6.3: Evolution of copper, gold and silver production throughout Mount Lyell's history. Source: Mudd (2009)

Table 6.2 gathers identified past practices that influenced the amount of mineral losses and their potential future recoverability.

Table 6.2: Practices influencing mineral losses and their recoverability in Mount Lyell

	MLMRC	CMT
Factors contributing to irreversible mineral losses	- Absence of containment of waste on site: AMD - Reactive mineralised material left exposed in-situ: AMD - Waste dumping in river	
Factors constraining future recovery	- Unstable and unsegregated waste rock deposit: safety risk in re-mining - Selective mining and increased cut-off grade	- Current care and maintenance
Factors facilitating future recovery	- Prince Lyell underground mine kept open: mining can resume	- Tailings contained in TSF: available for potential future reprocessing - Exploration work increasing knowledge of local resource

6.2. Results of MFA calculations

Results of MFA calculations for Mount Lyell are presented in Table 6.3 below. For comparison purposes, the values of MFA indicators from the Mount Morgan case study are also presented in Table 6.3. Indicators were calculated for the two main periods of Mount Lyell's life, characterised by the two mining projects. Total Production from Waste and Mineral Losses to New Waste are not presented in the table as none of the projects in Mount Lyell recovered minerals from waste.

Table 6.3: Values of MFA indicators for each mining project in both Mount Morgan and Mount Lyell.

	Mount Morgan			**Mount Lyell**	
	Historical Operations 1882-1982	*STR 1982-1990*	*Carbine Resources*	**MLMRC 1888-1994**	**CMT 1995-2012**
Years of operation	*100*	*8*	*8*	106	18
Total Production (TP) (M$)**	*10,200*	*510*	*520*	7,800	2,600
Annual Production (AP) (M$/year)	*102*	*64*	*65*	74	144
Total Production from Waste (TPW) (M$)	*0*	*510*	*520*	0	0
Total Material Processed (TMP) (Mt)	*50*	*28*	*8*	112	39
Material Processed Annually (MPA) (Mt/yr)	*0.5*	*3.5*	*1*	1.1	2.2
Total Material Moved (TMM) (Mt)	*140*	*28*	*14.6*	167	40
Material Moved Annually (MMA) (Mt/yr)	*1.4*	*3.5*	*1.8*	1.6	2.2
Net Waste Generation (NWG) (Mt)	*130*	*0*	*-2*	166	40
Material Efficiency (ME) ($/t)	*73*	*18*	*35*	47	65
Total Mineral Losses to Waste (TMLW) (M$)	*4,300*	*541*	*-380*	2,900	660
Irreversible Mineral Losses through AMD – 20 years (IML-	*Not available*	*Not available*	*Not available*	77	2.4

AMD) (M$)					
Irreversible Mineral Losses through dumping (IML-D) (M$)	*0****	*0*	*0*	2,500	0
Resource Left Behind (excl. waste) (RLB) (M$)	*0*	*0*	*0*	4,600	1,980
Extraction Inefficiency (EI) (%)	*30%*	*68%*	*21%*	49%	50%
New Area Impacted (NAI) (Ha)	*270*	*0*	*0*	2,800	246

** Colours are used to visualise the performance of each project relative to a particular indicator and compared with the other four projects. A negative performance is highlighted in orange, a positive performance in green, and a neutral performance remains uncoloured.*

*** The monetary unit used for all MFA calculations is US$.*

**** IML-D for Mount Morgan Limited is approximated to zero although some records show waste dumping practices existed in the early years of the mine (Boyle, R. F. & Gistitin 1992).*

6.2.1. Comparing Copper Mines of Tasmania and Mount Lyell Mining and Railway Company

MLMRC operated for a much longer period of time than CMT. However, CMT operations are approximately twice the size on average of the historical operations in terms of yearly material flows (Annual Production and Material Processed Annually). This was expected knowing that CMT increased the capacity of MLMRC's concentrator, which is thus able to process 2.5 million tonnes of ore per year (Cordery & Ritchie 2016). However, as Figure 6.3 showed before, this increase in production started before CMT and was gradual.

Because CMT operations are bigger in size, they also generate more tailings annually (see Table 6.3). However, CMT's underground operations generate significantly less waste rock than MLMRC's operations, which comprised both underground and open cut mining. This is mainly because underground mining generally minimises the amount of waste brought to the surface. In addition, the sub level caving mining method used by CMT is considered to be particularly efficient in separating waste rock and ore (Cordery 2016). CMT's higher Material Efficiency, and Total Material Moved and Net Waste Generation values which are less than twice those of MLMRC, can be attributed to these differences in the mining stage.

However, it should be noted that data available for the MFA calculations are not precise enough to evaluate accurately the influence of the mining stage on mineral losses and resource left behind. This is particularly relevant for Mount Lyell, where the various deposits were mined at different periods of time and with different mining techniques (e.g. underground mines tend to generate less waste but may leave more low-grade material behind than open cut mining). Ideally, data from each individual section of the complex ore body of Mount Lyell would be separated to calculate individual Material Efficiencies and Extraction Inefficiencies. This would allow accounting for differences in extraction strategy from one section of the ore body to another.

Total Mineral Losses to Waste are significantly lower for CMT, although this can be attributed to operations that had shorter durations. The two projects' TMLW cannot be compared in more detail as they are influenced by mineral processing recovery rates, which had to be assumed for MLMRC due to lack of data.

Irreversible Mineral Losses though AMD were calculated for a 20-year period (1995-2015) assuming that steady state was reached before 1995, which is a reasonable assumption according to Koehnken (1997). Koehnken states that the dumps were oxidising at a maximum rate, and were likely to continue producing acid drainage for greater than 600 years. IML-AMD results for CMT are adjusted to be three percent of the total AMD generated, according to estimations from the Acid Drainage Reduction Act (State of Tasmania 2003), which determined CMT's responsibility as part of the mine's overall environmental footprint.

CMT and MLMRC's Extraction Inefficiency (EI) results are similar, and close to 50%. This means that the value of minerals lost in the waste stream or left behind during the two projects is about the same as the value of production. The relatively high EIs (compared to other projects in Mount Morgan) can be attributed to high Resource Left Behind (RLB) values, which are included in the Extraction Inefficiency calculations. So far, CMT has been mining only a small portion of the remaining ore body, and if the operations were to stop now, it would leave significant amounts of resources behind.

These estimations can serve as a point of discussion on the theoretical scenarios presented in section 4.1.1, which the MFA indicators aim at visualising. In Mount Lyell, Scenario A corresponds to a life of mine that finishes at the closure of MLMRC. Scenario B corresponds to the actual life of the mine, including MLMRC and CMT, where CMT is a re-mining project as defined in Table 3.4. Scenario B contributes to enhancing resource recovery compared to scenario A, by lowering the Extraction Inefficiency from 49% in 1994 to 36% in 2012, and recovering US$ 2,600 million worth of minerals. And extended hypothetical scenario B would prolong the life of mine until all the Resource Left Behind is recovered, lowering Extraction Inefficiency to 20%. RLB and EI values exhibit the benefits of prolonging mining operations from the perspective of mineral resource conservation.

The positive contribution of scenario B, compared to scenario A, to the mine's environmental footprint, and to its overall eco-efficiency – the Production over Impact (P/E) ratio – is less obvious. CMT's operations most likely contribute to increasing the mine's environmental footprint, and do not contribute to removing any of the acid-generating material. CMT's Irreversible Mineral Losses through AMD was evaluated to be only three percent of the losses from the entire current AMD generation. However, this value, determined in the Acid Drainage Reduction Act, was possibly influenced by economic and political factors rather than based on a physical reality. There are no Irreversible Mineral Losses through Dumping for CMT, and overall CMT is expected – due to more stringent environmental regulations – to have considerably better environmental practices than MLMRC.

For the Material Efficiency indicator, which provides some indication about the eco-efficiency, scenario B would result in a small increase in material efficiency from 47 in scenario A to 50. The New Area Impacted (NAI) for CMT is also considerably smaller than MLMRC's. CMT is operating on already impacted land, and NAI for CMT, equals the size of the new tailings storage facility. If NAI were taken as a proxy of the mine's local environmental footprint (E) in the P/E ratio would be higher for scenario B than for scenario A. For scenario A (MLMRC alone), P/E would be equal to 2.8, whereas for scenario B (MLMRC and CMT up to 2012), would be equal to 3.4. If all the Resource Left Behind were to be extracted, P/E for an extended scenario B would increase to 4.1. Under these assumptions, the eco-efficiency of Scenario B could potentially be higher than that of scenario A. However, many other factors would need to be included in the environmental footprint to obtain a reasonable estimate of the eco-efficiency.

Overall, the results of MFA calculations for the two projects of Mount Lyell do not exhibit differences as striking as for the three Mount Morgan projects. A reason is that MLMRC and CMT are similar: they are both traditional mining operations, they extract the same commodities and use the same processing technology. There are, however, two main differences identified by the MFA indicators, those related to

a) the longevity and size of the operations (TP/AP, TMM/MMA, TMP/MPA, NWG, TMLW);
b) improvements in environmental and mining practices, where CMT performs better than MLMRC (IML-AMD, IML-D, ME, NAI).

The only indicators that do not fall into these two categories of results are Resource Left Behind and Extraction Inefficiency.

The other factor that makes any differences between the Mount Lyell projects less noticeable is the incomplete data, in particular the recovery rates for MLMRC, which affect Total Mineral Losses to Waste and Extraction Inefficiency.

6.2.2. Comparing Mount Morgan and Mount Lyell

Since Mount Morgan and Mount Lyell do not extract the same main commodity, the comparison between monetary indicators, which express an aggregated value of several metals or minerals, should be done with caution. In particular, a comparison of the two sites would benefit from including more data on the economics of each project (e.g. pre-production capital costs and operational costs). However, some observations can be made here.

The monetary indicators (Total Production, Total Production from Waste, Total Mineral Losses to Waste, Extraction Inefficiency, Irreversible Mineral Losses through AMD and Dumping, Resource Left Behind) provide information on the economic value being recovered, left behind or lost. They exhibit important differences between the two sites and individual projects. Firstly, production values between the two historical operations show that Mount Morgan's revenues were higher. Comparing production values, the marginal character of the two waste reprocessing projects in Mount Morgan is also highlighted, and CMT, as a re-mining project, manages to make significantly more value on a yearly basis.

Irreversible Mineral Losses through Dumping (US$2.5 billion) and Resource Left Behind (RLB) (US$4.6 billion) values show how significant dumping practices and incomplete mining are relative to Mount Lyell's production values (US$7.8 billion). Extraction Inefficiencies (EI) for Mount Lyell are dominated by high RLB values, whereas mineral losses to waste are the determining factor for EI in Mount Morgan. If RLB was to be excluded from EI calculations, MLMRC's EI would be at 36%, similar to Mount Morgan's historical operations.

Differences in the main commodity extracted also affect the comparison between bulk material indicators, as it implies different average grades and thus differences in the tonnage of material to be moved or processed. In particular, mining of one kilogram of gold would require more material moved and processed than mining of one kilogram of copper. A careful comparison of Mount Morgan and Mount Lyell's Total Material Processed, Total Material Moved and Net Waste Generation shows that copper mining in Mount Lyell generated, and still generates more material movement than gold mining in Mount Morgan. This, and the lower Material Efficiency values in Mount Lyell compared to Mount Morgan's historical operations, indicates that Mount Lyell's operations recover less economic value for more material moved. This could be due to a variety of factors, including a more complex ore body in Mount Lyell, which required several open cuts and various underground workings.

Compared to the two reprocessing projects in Mount Morgan however, CMT's Material Efficiency is high, and this is explained by low production values from the STR and Carbine projects. This suggests that waste reprocessing may in this case generate less value than a traditional mining project, possibly due to lower grades.

Total Material Processed and Material Processed Annually results also indicate that Mount Lyell's operations are larger in size, with MLMRC processing twice more material yearly than at the same period of time in Mt Morgan. The difference in size is also visible in the New Area Impacted (NAI) of mining operations, which is ten times larger in Mount Lyell. Although CMT has been operating for less than twenty years, its NAI is close to Mount Morgan's overall NAI.

Differences in Total Material Processed (TMP) between the two sites are more important than Total Material Moved (TMM) and New Waste Generation (NWG). This means that the amount of waste rock in Mount Morgan is significantly higher than in Mount Lyell. Overall, higher TMM, TMP, NWG and NAI values in Mount Lyell suggest a higher environmental footprint linked to mining activities. Estimations of AMD generation also confirms Mount Lyell's impact is significantly higher. This would need to be complemented with impacts related to mineral processing, which may exhibit interesting differences as gold processing would be more energy intensive due to lower grades.

It should be noted that the comparison of New Area Impacted value brings the issue of the evolution of waste management practices. CMT's tailings storage facility is complying with environmental regulations, and covers a large area, which results in a higher NAI than for example the STR project. It is likely that the STR project's waste management plan would not be compliant nowadays.

Overall, Mount Lyell and Mount Morgan exhibit similar characteristics, notably in their exceptionally long life, the new projects starting in the 1980s and 1990s, and the significant environmental legacies due to large amounts of acid generating material. However, the significant differences between Mount Lyell and Mount Morgan's history are reflected by the MFA indicators. In particular, Total Production from Waste is null for Mount Lyell and Irreversible Mineral Losses through Dumping and Resource Left Behind are null for Mount Morgan. Also because of the absence of waste reprocessing in Mount Lyell, Mineral Losses to New Waste and Total Mineral Losses to Waste are equivalent on this site.

The main difference between Mount Morgan and Mount Lyell is that the former is a gold mine, and the latter a copper mine. Comparing the MFA results is limited, and it would be more informative to compare sites with more similarities. Because each mine site is unique and MFA results are influenced by ore body characteristics, it would be valuable to apply them on a larger number of sites, and thus establish a baseline on which the performance of new projects can be assessed.

In addition, data quality may vary from one site to another. For the two case study sites, a clear example is that data related to pyrite content in Mount Lyell were not available, hence not included in the MFA. More generally, available data for Mount Lyell are characterised by a higher level of detail for the production values, while in Mount Morgan provides more information on waste amounts and composition. These differences affect assumptions taken in MFA calculations as well as final results (see Appendices I and II).

6.2.3. Reviewing scenario C for Mount Morgan and Mount Lyell

Scenario C in section 4.1.1 is described as an ideal scenario where sources of inefficiencies and mineral losses would have been prevented from the start of the mine's life. It is worth connecting the case studies findings with the theoretical considerations in Chapter 4, although the data does not allow making a quantitative comparison. As mentioned in sections 5.2.1 and 6.2.1, Mount Morgan and Mount Lyell's life cycle are examples of scenario B, with reprocessing and re-mining projects extending the lives of the mines.

In a hypothetical scenario C, mineral losses through dumping and acid mine drainage would have been avoided. Contained within the mine's boundaries and stored adequately, a portion of these minerals could have been recovered through an additional processing or reprocessing stage. A reprocessing stage would also have efficiently minimised the Mineral Losses to Waste. In Mount Lyell, Resource Left Behind would be close to zero. As a result, Extraction Inefficiency would be minimised in both sites.

Material Efficiency (the Production over Total Material Moved ratio) may not be maximised in a hypothetical scenario C, as more processing and reprocessing necessarily involves more material moved. The aim is not to maximise this ratio, but rather optimise it by balancing it with other factors such as, for example, energy use. The same consideration applied to Total Waste Generation, which would remain high if mineral extraction were to be maximised. Total Waste Generation could be reduced if downcycling uses for the waste were found.

A scenario C occurring in Mount Morgan or Mount Lyell would potentially lead to very different MFA results. However, these considerations remain hypothetical, and the real potential for scenario C should be estimated while knowing the economic and technological realities of the mining industry.

6.3. The future of Mount Lyell

Similar to section 5.3 for Mount Morgan, this section collects qualitative information from the site's history and current situation that was not captured by the MFA indicators. Combining this analysis with the relevant MFA results, an assessment is presented on the barriers and enablers for an extension of the mine's life that would enhance mineral recovery and increase environmental remediation.

For Mount Lyell, this potential extension should currently include CMT, which could potentially continue mining the ore body for several years. This may result in reducing some of the AMD generation from underground workings by removal of the reactive material, which is a significant part of the AMD source. However, CMT is not responsible for any of the past legacies, and, unlike the arrangements between the Queensland government and Carbine Resources on the extraction of pyrite, CMT is not involved in any remediation work outside of its own activities.

Because of these differences, the section is organised in a different way compared to section 5.3. Since there is no waste-reprocessing project in Mount Lyell, there cannot be an assessment of strengths and weaknesses on such project. Instead of that, section 6.3.1 investigates opportunities and threats for the potential development of a waste-reprocessing project, either in collaboration with CMT or another party. Waste may either be liquid (i.e. AMD) or solid. Then, section 6.3.2 discusses general opportunities and threats for prolonging mining operations with CMT, and the challenges it may face in recovering remaining parts of the ore body.

Information gathered in this section was partly collected through personal communication with Geoff Cordery, Environmental Manager at Copper Mines of Tasmania, and Jennifer Parnell and Coleen Cole from the Tasmanian Government (Cole 2016; Cordery 2016; Parnell 2016).

6.3.1. Opportunities and threats for the development of a waste reprocessing project

An agreement between CMT and the State – the Mount Lyell Acid Mine Drainage Reduction Act (State of Tasmania 2003) - ensures CMT would have to allow a third party on site to treat the AMD. This opens opportunities for potential future waste and wastewater treatment businesses to access the mining lease.

However, conditions in Mount Lyell are not as favourable for the development of a waste-reprocessing project as they are in Mount Morgan. A first significant barrier is the dumping practices that make most of old tailings and slag unrecoverable. About two thirds in weight of all the waste generated during the historical operations was lost. In terms of mineral content, the proportion lost is higher: out of the US$2.9 billion worth of Total Mineral Losses to Waste, US$2.5 billion was dumped. Most of the waste remaining on site is waste rock, which would likely require energy intensive grinding prior to further processing.

Compared to the historical operations in Mount Morgan, which left a Total Mineral Losses to Waste of US$4.3 billion, there is therefore only US$400 million left on site by MLMRC, plus US$660 million of TMLW from CMT. A waste-reprocessing project in Mount Lyell would also not be able to rely on gold production, which would be the most important source of revenue for Carbine Resources in Mount Morgan.

Similar to Mount Morgan, minimum effort was spent on waste management during the historical operations. As a result, little data is available on the composition or age of the various waste dumps – 22 in total according to the Sustainable Development Advisory Council (SDAC) (1995) – and waste was disposed in an uncontrolled manner. The largest of these dumps forms a steep hill that represents a potential safety issue, and contains pieces of old machineries and discarded tyres that were mixed together with waste rock. This single waste dump is responsible for about 21 % of the AMD generation (Koehnken, 1997), which makes it also a challenge for remediation.

On the other hand, the complex mineralogy of the Mount Lyell ore body may allow for recovering other metals whose values were not included in MFA calculations, such as zinc - 4 to 5% zinc left in slag from Iron Blow - or cobalt from CMT's tailings (Cordery 2016). Similar to Mount Morgan, Mount Lyell also exhibits high pyrite concentrations, and recovering pyrite from the tailings storage facility would decrease tailings' tonnage by about 10% and make it more benign. However, the pyrite market might be difficult to access from an isolated site such as Mount Lyell.

The particularly wet weather conditions in Mount Lyell also suggest that focus could be set on AMD waters rather than on solid waste itself. Daily AMD flow leaving the mine site is of about 19000 m^3, i.e. approximately twenty times more than in Mount Morgan (Koehnken

1997; Wels, Findlater & McCombe 2006). However, Mount Lyell does not have a seepage interception system, nor does it have a water treatment plant. Seasonal variations in water flow volume and composition would make it challenging to operate a water treatment plant continually (Cordery 2016). Irreversible Mineral Losses through AMD were estimated to be of nearly US$80 million in a 20-year period. While this is a small amount compared to CMT revenues, or even Carbine's revenues, AMD flow is rather well channelled through Haulage creek, which gathers 98.7% of the copper load entering the Queen River (Koehnken 1997) making a collection system relatively easy and efficient to possibly economically recover copper minerals. In Mount Morgan, Carbine Resources plans to make use of the mine water in its processing operations. A similar arrangement could be implemented in Mount Lyell, where water needs to be pumped out of the underground while the mine remains open, and could be the feedstock for a water treatment/reprocessing plant.

However, it is worth noting that the Queen and King River system is impacted so heavily that a significant improvement would occur only if a drastic change – namely more than 98% of AMD diverted - were to occur upstream (Koehnken 1997). This makes it highly challenging for a potential AMD treatment project to be successful.

Overall, it appears that there is currently not enough incentive to address the environmental remediation of the Mount Lyell site by actively treating and reprocessing liquid or solid waste. It also seems that a waste-reprocessing project in Mount Lyell would struggle to be economically feasible. This is confirmed by several failed attempts at proposing a stand-alone treatment of AMD (Cordery 2016; Parnell 2016). One attempt however came close to succeeding. In 2003, a pilot plant, using copper cementation and precipitation, was built by the State. It was estimated that 1000 tonnes of copper per year could be recovered (Parnell 2016). However, the cementation process releases one ferrous ion for every copper ion it extracts from solution. Therefore, although the plant would be successful in recovering some of the lost copper, it would not solve the river contamination problem.

Nevertheless, opportunities for collecting AMD and coupling its treatment with other mining and mineral processing activities happening on site would be worth exploring. This however means CMT would be involved, and currently CMT has no obligation to do so, as it is not being held responsible for any of the past environmental damage. This would have had to be negotiated differently by the Tasmanian government prior to CMT's project start.

6.3.2. General opportunities and threats for prolonged mining operations

Although it is still unclear whether there would be a way to economically recover minerals from either solid or liquid waste in Mount Lyell, there is no doubt significant reserves are left in the ore body: Resource Left Behind is currently of nearly US$2 billion, and this value may increase with more exploration. CMT's operations are currently covering a small portion of the remaining ore body, and the company has been exploring other areas of the mining lease in parallel.

Similar to Mount Morgan, numerous past investigations – originating from both government and industry initiatives - have increased the knowledge of the site, both in terms of its environmental footprint and of its remaining resources (e.g. CMT 1995; Euralba Mining 1992; Morrison, Wills & Cordery 1995; Newnham 1993). The University of Tasmania is also involved through its own research, mostly in the area of environmental remediation.

Data from past MLMRC operations are available, and provide information on remaining resources (Cordery 2016). These may be found surrounding old underground workings or open pits, or in currently unmined areas of the mining lease. Based on this information, CMT considered turning Mount Lyell into a super pit, recovering the remaining resource as part of a larger operation (Koehnken 1997). However, this plan is not progressing at present.

Both government and CMT representatives are concerned about the risk of exacerbating AMD generation by excavating more material and thus exposing more reactive material to rainfall and surface water (Cole 2016; Cordery 2016). This concern is emphasized by the presence of the Macquarie Harbour downstream of the site. Since 1982, the World Heritage Listed Tasmanian Wilderness National Parks includes a portion of the Macquarie Harbour, located downstream of the Queen and King river system impacted by Mount Lyell's mining activities (SDAC 1995). In 1997, it was estimated that pollution originating from Mount Lyell only had a small contribution to the state of Macquarie Harbour

(Koehnken 1997). New mining activities on site could however have a greater effect on the harbour.

This results in a general reluctance to consider moving any material from parts of the site that are currently abandoned, e.g. the Iron Blow pit and the water it contains. CMT may be restricted in the area accessible for mining also due to safety issues and unstable surface and underground structures remaining from MLMRC’s operations.

The short-term future of CMT is also uncertain. CMT has been on an extended care and maintenance period since 2014 due to low copper prices (Cordery 2016). Care and maintenance activities involve pumping water out of the underground mine operated by CMT, which represent a cost for the company and cannot go on indefinitely. Stopping the pump would result in natural flooding of the underground workings, and would mean a possibly irreversible closure of this area of the mine site. This situation makes the reopening of the mine more urgent than in Mount Morgan where the abandonment period has been for over 25 years.

The government of Tasmania is conscious of that pressing need, and has been facilitating CMT’s project since the beginning. To ensure CMT would take on the mining lease, the CMT agreement (Thomas 1994) signed by both parties released CMT from any obligation related to past legacies. This supports the continuation of mining activities by reducing some costs, but it is a disadvantage in regards to the need for remediation. This is discussed further along with the recent governmental support in Mount Morgan in Chapter 7.

To conclude, both the short-term and long-term futures of CMT in Mount Lyell are currently uncertain. It seems unlikely that CMT will be able – or willing - to extract all the remaining resource in the ore body due to its complexity as well as poor management in the past. This means that environmental remediation is also unlikely to occur as a result of displacement of reactive material. This is especially true if pyrite, the most common acid generating material, is not targeted for extraction.

6.4. Conclusion

This chapter presented the case study on Mount Lyell in Tasmania. The application of the MFA indicators provided some insights into the performance of the two mining projects in Mount Lyell. In particular, it provided quantitative results related to the projects' production, environmental footprint, and eco-efficiency, and more specifically to waste generation and permanent losses of minerals.

The application of the MFA indicators allowed for evaluating the contribution that the Copper Mines of Tasmania, as a re-mining project, is currently making to resource recovery and environmental remediation on site. The results show that, while CMT is making a positive contribution to resource recovery, it currently still leaves significant amounts of resource behind. As for its contribution to environmental remediation, and despite the certain positive evolution in environmental practices, CMT's contribution is limited.

The application of the MFA indicators to Mount Lyell relate to the secondary research question b): "how does such a change in waste management practices improve the overall metabolism of a mine site, and how can this improvement be measured?" In the case of Mount Lyell, the MFA indicator set allowed for estimating the potential improvements that a re-mining project can make. CMT's re-mining activities contribute to reducing the amount of resource left behind, and thus support the "reduction" highest level of the Mine Waste Management Hierarchy as presented in Chapter 3. Mount Lyell did not exhibit any waste reprocessing or waste downcycling activities.

The attempt at comparing MFA results for Mount Morgan and Mount Lyell exhibited some potential issues with site-to-site comparisons. The first issue relates to the monetary indicators: while they allow comparison based on a common unit, they may lose physical meaning. Another type of aggregation could be sought, for example by using a weighing factor that expresses the abundance (or the criticality, see 7.3.1) of a particular mineral. This also points out the need to apply the indicators to a larger sample of mines in order to establish a baseline and allow for more rigorous comparisons.

The perspective on the past and future of Mount Lyell showed that opportunities to move forward and increase resource recovery from the site while making a positive contribution to the site's environmental state were limited. The two issues have been disconnected by two separate agreements between CMT and the government, one releasing CMT from responsibility over past environmental damage, and the other authorizing the involvement of a third party for environmental remediation. Comparing the value of what is produced by CMT and the AMD value lost during a 20-year period, this leaves little option for a stand-alone AMD treatment project to be economically successful.

In terms of minerals remaining on site, the majority is in the ore body, and there are few viable options for reprocessing of waste. Opportunities for extracting remaining parts from the ore body and prolonging mining activities on site are however constrained by the state of the site and the risk of making things worse.

7. Policy incentives for a more sustainable management of mineral resources

This chapter aims at studying the role of governments in fostering mining practices for delivering better sustainability outcomes that align with industrial ecology concept. In the context of this thesis, these practices should produce an enhancement of mineral recovery coupled with waste minimisation and environmental improvements.

The chapter starts with a reflection on the role of governments in mining activities, in particular, where their interest lies, and why their role makes their contribution essential. This first section uses a publication from Hunter (2014) as a support to build on. Hunter (2014) was the most relevant reference on this topic from only a small number of related papers that were identified, and discusses nation-wide approaches to maximise resource recovery from oil reservoirs, comparing Australia and Norway.

Section 7.2 then presents the main findings on the governments' involvement in the case studies of Mount Morgan and Mount Lyell within the national and state-level contexts. These findings help identify some key issues and areas of improvement. Based on that, section 7.3 then proposes general pathways for changes in the Australian mining policy. For information on the methodology adopted for data collection for this analysis, refer to section 4.5.

7.1. The government's involvement in mining

Hunter (2014) studied the role of the government in the development of petroleum resources. Some of her work's findings are transferable to other non-renewable natural resources such as mineral resources.

Hunter points out that, by nature, the relationship between governments and extractive industries is a relationship of "interdependence with diverging interests". The interdependence is visible in the industry's investment choices, which influence employment, tax revenue and GDP growth. Governments on the other hand, are the owners of the land and grant access to this land, while representing the collective will of their citizens. The diverging interests are observable on the geographic level, as mining companies' strategies focus on their portfolio, which is either local or international, whereas the governments' interest is with the national resource. More importantly, governments are concerned with ensuring socio-economic benefits for their people, whereas the companies' imperative is to maximise their own profit. Because these interests diverge, the role of the government in resource development is paramount.

By convention, the state makes and enforces laws within the country. The primary role of governments is through its policy framework. Because of the interdependence stated earlier, one of the resource policy framework's main aims is to favour and secure investments in the mining industry, that is to say make the country attractive for private investments and provide the right encouragements for mining companies to extract the resource from the ground. However, the state's responsibility is also to make sure this industrial development happens in a way that the value of a nation's natural resources is maximised and fairly distributed to the country's people, now as well as for the generations to come. This requires a wider and longer-term perspective than that of private companies, a perspective that takes into account the finitude of the resource.

In particular, a successful resource policy should include rules around the efficiency of extraction, in terms of how a mining project manages to maximise value and minimise waste from a particular ore deposit. Hunter (2014) argues that governments need to provide clear directions for companies to extract the optimal amount of petroleum from a deposit. Otherwise, the operator is likely to extract the petroleum at as low a cost as possible, and to abandon the field when profitability becomes marginal.

From the policy framework are derived various kinds of policies, regulations or programs, with which the state can influence the mining industry. The most common response to environmental impacts caused by the industry in general has been through regulations (Howes 2013), in particular by imposing standards or technologies. Both Howes (2013) and Ehrenfeld (1994) point out that regulative rules are often rules that constrain industrial activities by closing possibilities and narrowing down the options rather than opening new opportunities, which has a significant drawback - although they also lead to noticeable improvements. They can lead to resistance from the industry, which is not compelled to go beyond simple compliance, and somewhat inhibit its innovative function.

However, there is a wide range of possible government interventions. Some are rather direct or active types of interventions, while others are more indirect or passive, and they vary significantly from one country to another. Hunter (2014) observed the Norwegian government's involvement in petroleum extraction, and argues that its active participation as direct investor has given it the ability to require improved recovery rates and prolonged production in a particular deposit.

After these preliminary considerations on why and how governments can be involved in mineral extraction and influence industrial practices in this area, this chapter focuses more specifically on the findings from the two case studies, Mount Morgan and Mount Lyell presented in Chapters 5 and 6, with their respective state governments Queensland and Tasmania (see 7.2).

The chapter then provides a discussion on what could be a more suitable and successful type of government involvement in the Australian mining industry, using findings from previous chapters as well as additional findings from the case studies in Mount Morgan and Mount Lyell. This discussion does not intend to conclude with a defined set of policy measures, which would require a more in-depth analysis of Australia's economic, social and political system, as well as a comparison with other countries' policy frameworks, but rather provide some relevant observations and potential lines of future research.

Section 7.2 gathers the additional case study findings, and critically describes the governments' involvement through the life of Mount Morgan and Mount Lyell. This is introduced by placing these findings within the national and state-level backgrounds. Section 7.3 uses the conclusions of 7.2, as well as the previous chapters of this thesis, to suggest improvements to the current contribution of the Australian state governments in promoting a better sustainability performance for mining industry.

7.2. Case study findings

7.2.1. National background

In Australia, the Federal Government sets national policy including fiscal, monetary and taxation policy. Government involvement in Australia is different from the Norwegian example mentioned earlier, as the government does not invest directly in mining operations, or engage in any commercial exploration and development. However, it invests in the collection of pre-competitive geoscientific data, which provides information on the nature and size of known ore deposits, and thus facilitates mineral and petroleum exploration (Geoscience Australia 2015).

Keeping in mind this background of limited involvement and authority from Australia's federal government, it is worth reviewing two nation-wide reports concerning mining practices. Firstly, the Guide to Leading Practice Sustainable Development in Mining, published by the Department of Industry, Innovation and Science, is composed of an introductory report that acknowledges the need to include the natural resource conservation in sustainability considerations (Laurence et al. 2011).

The chapter on tailings management includes a short section on tailings minimisation, recycling and reuse, which mentions the need to prioritise waste minimisation and include waste reprocessing as part of mineral waste management options (Laurence et al. 2011). The report also warns against resource sterilisation that occurs when downcycling metal-rich material, namely using it as backfill. More generally, it states that "the disposal of tailings in a way that will make tailings recovery or re-treatment uneconomic, or prevent future mining activities is often actively discouraged" (Laurence et al. 2011).

Finally, the chapter on mine closure highlights the negative effect of premature closures on resource left behind (LPSDP 2016a). The closure chapter also raises awareness on mining companies' responsibility towards environmental remediation. It advocates for an appropriate system of security bonds, which secure sufficient funding for rehabilitation, even when a mine's operator is experiencing financial difficulties in completing the life of mine along with all the rehabilitation requirements.

However, the guidelines remain overall general, notably lacking practical examples of waste minimisation and prevention of mineral losses. Besides, the structure of the LPSDP guidelines, which are divided into different books such as Tailings Management (LPSDP 2016d), Mine Closure (LPSDP 2016a), Managing Acid and Metalliferous Drainage (LPSDP 2016c), and Mine Rehabilitation (LPSDP 2016b), does not highlight the interconnectedness of these issues.

A second noteworthy report, although fairly old, comes from the National Strategy on Ecologically Sustainable Development (NSESD 1991) and its working group on mining. It is cited in the Sustainable Development Advisory Council's report about the CMT project in

Mount Lyell (SDAC 1995). In this report, the authors raise the issue of compromised access to economic resources because of bad practices, notably during the closure stage, and recommend defining specific requirements upon the issuing of mining leases. In the later final report (NSESD 1992), one of the three stated objectives concerning the mining sector is to provide appropriate community returns from mineral resource extraction while improving environmental management. As part of that objective the government should engage in pursuing strategies to improve mining practices in the area of resource loss from abandoned mine sites, and other inefficient mining practices.

7.2.2. State level - Queensland and Tasmania

National objectives are however more likely to be practically implemented at the State and Territory level. In Australia, States and Territories have a direct influence on mining practices as they are in charge of managing and allocating mineral property rights, regulating operations (including environmental), collecting royalties, and have primary responsibility for land administration (Geoscience Australia 2015). Each of the States and Territories owns the mineral resources within its borders, and has its own related legislation.

This section focuses on the two States where the case studies are located, Queensland and Tasmania. Both Queensland and Tasmania are significant mining states, with a long mining history as well as currently active world-class mines (Geoscience Australia 2015).

In both states, two main agencies regulate mining activities. The Department of Environment and Heritage Protection (DEHP) in Queensland, and the Environment Protection Authority (EPA) in Tasmania, regulate the environmental footprint of mineral extraction. The Department of Natural Resources and Mines (DNRM) in Queensland, and Mineral Resources Tasmania (MRT) within the Department of State Growth, regulate the financial and administrative side of mining activities, and are notably in charge of attracting investments, delivering licenses, and collecting royalties. Coherence between environmental and economic development goals in mining would first require a strong relationship between the two types of agencies.

The state governments play a decisive role during the mining project's approval process. Amongst other application forms, mining companies are required to submit an

Environmental Impact Statement (EIS). The EIS guidelines defined by the Queensland government (DEHP n.d.) require to review strategies that avoid and reduce waste as well as reuse and recovery options to minimise the environmental impact of waste disposal.

To protect themselves from the costs of premature closure where the operator is financially unable to complete the rehabilitation, Australian states and territory have adopted a system of financial assurance, which may be included as a condition of the Environmental Authority (State of Queensland 2017b). A bond can thus be paid in advance by the company, which the state can use if needed.

In Queensland, the application of the financial assurance is currently being re-examined, as shows the discussion paper produced by the Queensland Treasury (State of Queensland 2017a). The paper starts with noting the current state of mine site rehabilitation, which stands at a low 9% of all the land disturbed by mining activities in the State, and asserting that financial means should be secured to increase that rate in the future.

Additionally, state governments are finding new ways to be able to hold individuals and companies responsible for the environmental damage caused (Wilson 2016). Recently in Queensland, an amendment to the Environmental Protection Act called the Environmental Protection (Chain of Responsibility) Amendment Act 2016 has taken effect (State of Queensland 2016). This amendment would notably allow the government to hold accountable the owners of sites that are in financial difficulties and make sure they do not bypass their environmental obligations (EDO Qld 2016).

Finally, for Mount Lyell, because of its exceptionally long history and the extent of their environmental legacies, a state agreement was also developed and signed by both the new operator (CMT) and the government of Tasmania. This type of agreement allows for a special arrangement - administrative, financial, operational and environmental - that is adapted to the specificity and the importance of a particular mine site, and which can be negotiated by the mining company (SDAC 1995). It notably offers the possibility to override other existing legislation. This agreement defined CMT as a project of state significance. State agreements are also used in Western Australia, but are no longer used in Queensland (Cabas 2017).

7.2.3. Government involvement in Mount Morgan and Mount Lyell

At the mine site level, Mount Morgan and Mount Lyell's history reflects the influence of government involvement.

- Evolution in mining practices following evolution in environmental regulations

The two century-old case-study sites are well suited to observe how change in practices correlates with change in regulations. The evolution and the toughening of environmental regulations for the Australian mining industry have led to improvements in waste management and environmental remediation practices, both in Mt Morgan and Mount Lyell. Waste dumping was banned, and consequently stopped in the first half of the 20th century in Mount Morgan (Boyle, RF & Gistitin 1992), while it stopped much later, in 1994, in Mount Lyell. However, Mount Lyell stands out as an exception in Australia (Mudd 2009).

Later on, Mt Morgan's historical operations started a rehabilitation program as well as pollution control measures (Boyle & Gistitin 1992), although it still generated high amounts of reactive waste without providing proper containment.

Today, operations like CMT are equipped with state-of-the-art tailings storage facilities and comply with the ISO14001:2004 requirements for environmental management systems (Cordery 2016). The conditions for the Licence to Operate Scheduled Premises issued by the SDAC included the implementation by CMT of a waste management system in accordance with the waste hierarchy: waste minimization, waste reuse or recycling, waste treatment, waste disposal (SDAC 1995), which - to a lesser level of detail, resembles the hierarchy developed in Chapter 4. In terms of practical implementation of this hierarchy, CMT argues that its mining method called "sub level caving" offers a high production rate while minimising the amount of waste rock (Cordery and Ritchie 2016). CMT's mineral processing plant is designed for high recovery rates, thus minimising the amount of copper in tailings. However, it is unclear whether reuse or recycling options for mining waste have been investigated, and all of CMT's mining waste is either transferred to the TSF (after being treated with lime) or to a waste rock dump for final disposal (Cordery and Ritchie 2016).

Additionally, CMT continued exploration for remaining ore in other areas of the mining lease. Pre-feasibility studies are on the way for recovering ore left behind from earlier mining activities (Cordery and Ritchie 2016). However, CMT's achievements cannot progress at present now that the site is placed on care and maintenance.

- The issue of premature closures

The advancement of environmental practices that occurred during Mount Morgan Limited's long lasting operations was compromised during the STR project (Boyle, RF & Gistitin 1992). The change in ownership resulted in a change of both mining strategy and environmental management, with the rehabilitation program started by Mount Morgan Limited abandoned by the STR project.

The other major consequence of the change in ownership was that the last owners of Mount Morgan were released from all responsibility towards further environmental remediation. An agreement between the State and Mount Morgan Limited was signed in 1991, where the government acknowledged that, given the site's long history, current shareholders that had been involved in the management of the mine since only the end of 1988, should not be held responsible for past environmental damage (State of Queensland 1991). Indeed, Elders Resources Limited and Carter Holt Harvey Limited, the last two companies on site, took over the operations at a time when the project was already generating significantly less profit (Boyle, RF & Gistitin 1992). Before that, Peko Wallsend Limited, the company present at the start of the STR project, had been operating since 1968 (MMPAD 2014).

As previously mentioned in Chapter 5, the nature of the STR project later caused further problems and worsened the situation for the Queensland government. The first years of the project were generating significant profits. However, after successive changes in ownership, the last company at the site was the least profitable, yet it also had the total costs of the STR project's rehabilitation to manage. Carter Holt Harvey Limited was in the end unable to implement its rehabilitation objectives and the mine was subsequently abandoned (Boyle, RF & Gistitin 1992). Despite that, over the STR project's history, mining practices were in compliance with environmental requirements. In particular, the successive owners respected the water discharge limits to the river (Boyle, RF & Gistitin 1992; Wels, Findlater & McCombe 2006).

A few years after these events in Mount Morgan, the closure of Mount Lyell in 1994 was planned. However, in practice, certain elements indicate the closure was rather premature. Two agreements between Mount Lyell and the State of Tasmania, from 1985 and 1992, show that MLMRC was eager to cease the operations, while the State of Tasmania was attempting to prolong them (State of Tasmania 1985, 1992). Mount Lyell was at the time a wholly owned subsidiary of Renison Goldfields Consolidated, which left the site at the end of 1991. The 1992 agreement between Mount Lyell and the State of Tasmania required the remaining operator of Mount Lyell to continue operating until the completion of Prince Lyell underground mine (State of Tasmania 1992). At the closure in 1994 however, there was still material left in the Prince Lyell ore body (causing significant AMD), which CMT continued to mine from 1995 (CMT non dated). Furthermore, exploration work done by CMT confirms there was additional economic resource on other parts of the mining lease.

At the closure in 1994, rehabilitation work was not completed either. In particular, the West Lyell Waste Dump, responsible for 21% of all AMD leaving the site (Koehnken 1997), was left untouched. Finally, the 1994 closure was well-ordered, with no anticipation for future operations, making it a significant challenge for CMT to reopen the site (Cordery 2016).

The MLMRC was nonetheless required to leave AU$1.5 million fund to the State Government to be used toward the remediation of the site (Koehnken, 1997). This was an insufficient amount: as a matter of comparison, on a smaller site such as Mount Morgan, the DNRM spent more than AU$20 million between 2004 and 2015 for its rehabilitation (Dann 2016). AU$2 million yearly are required to operate Mount Morgan's water treatment plant. In spite of these efforts, site discharges from Mount Morgan still has not reached acceptable levels (Wels, Findlater & McCombe 2006).

Mount Lyell and Mt Morgan are particularly striking examples, and are likely to be two of the most problematic environmental legacy cases in Australia. Because of the mines' exceptional longevity, the Queensland and Tasmania governments struggled with the complexity to address the environmental damage caused at a time when environmental regulations were less stringent than currently.

However, the two main events just described, i.e. the poor practices during the STR project and the following premature closure, and the 1994 closure of Mount Lyell, show certain deficiencies in the governments' involvement at the time. In particular, the State Governments did not have enough leverage to ensure the continuation of operations in Mount Lyell and the continuation of the rehabilitation program in Mount Morgan. The examples of the STR project and the 1994 closure of Mount Lyell are also signs that some mining companies certainly at the time avoided taking reasonable responsibility for their environmental impact.

- Economic incentives and environmental costs

At the same time, the State governments did make substantial efforts to reopen or keep these mines open. In both Mount Lyell and Mount Morgan, the governments were active in searching for new operators, which aligned with the national guidelines on avoiding resource sterilisation. The agreement with CMT also ensured CMT's mining strategy and extraction methods would not generate further resource sterilisation (SDAC 1995). This included the location of new waste deposits.

In the aim of prolonging operations in Mount Lyell, the government went so far as to provide economic incentives, such as the AU$25 million in royalty discounts mentioned in Chapter 6, as well as temporary loans in the 1970s, at a time when MLMRC was having financial difficulties (SDAC 1995).

However, the government of Tasmania had no funds available for rehabilitation of Mount Lyell. This disparity between the economic and environmental aspects is also visible in the agreement with CMT (State of Tasmania 2003), which, similar to the situation in Mount Morgan, declared that CMT was not responsible for "any pre-existing and ongoing contamination and pollution caused by previous occupation or use of the Leased Land" (SDAC 1995). In particular, this allowed CMT to continue discharging AMD water in the river, without prior treatment or approval under the Environmental Protection Act 1973. The significant governmental support for the continuation of mining activities in Mount Lyell therefore appears to leave environmental concerns unaccounted for.

However, this absolving of responsibility that occurred in both Mount Morgan and Mount Lyell seems to have been a determining incentive to attract the new operators and thus prolong operations. In that sense, this was a necessary compromise for an enhanced resource recovery. The government of Tasmania was particularly eager to prolong Mount Lyell's life to avoid the environmental consequences of a premature closure (SDAC 1995).

In Mount Morgan, the Department for Natural Resources and Mining (DNRM) had the financial means to undertake urgent short-term measures for safety and pollution control. Out of the AU$20 million spent between 2004 and 2015, AU$8 million were spent in 2004 on decommissioning three historical tailings dams in the Dee River that presented a high risk of failure. This involved the relocation of 460,000m3 of acidic tailings to the open cut pit (Dann 2016). Though these measures were deemed too urgent to delay further (McCombe 2009), the relocation was not coupled with any treatment of the reactive tailings, or part of a resource recovery project. Neither the water treatment plant nor Carbine Resources' project existed at the time. Disposal in the open cut pit resulted in dilution of the mineral content, making potential future recovery more difficult.

This disconnection between costly environmental remediation efforts and the governments' willingness to provide economic incentives for the continuation of the operations is relevant, and worth highlighting. This suggests that both industry and government are still treating environmental impact mitigation as an economic burden. In the case of Mount Morgan and Mount Lyell, this disconnection may also be attributed to a discernable lack of economic solutions, given the exceptional extent of the environmental legacies and the current global market. The government's reaction came too late, compared with the long history of the two sites, and in retrospect prevention measures could have been more successful. Both in Mount Morgan and Mount Lyell, the government's response was reactive and limited in scope and means.

Both academics and practitioners agree that most effective actions to mitigate a mine's environmental footprint are preventive and proactive, and should be incorporated early on in mine planning (e.g. McLellan et al. 2009; Moran & Kunz 2014). Coleen Cole, manager at the Environment Protection Authority of Tasmania, confirms that remediation and rehabilitation programs are successful in other mines in Tasmania, such as in Savage River, where the mine is still operating and tailings are being neutralized prior to disposal (Cole 2016). Opportunities to undertake effective and durable actions diminish considerably as mines get closer to the end of their life when there is a key focus on reducing costs.

- Emerging innovative business models

Carbine Resources' project shows how the economic and environmental spheres are interrelated, and demonstrates that waste reprocessing can potentially satisfy both, in collaboration with the government. However, Carbine is experiencing difficulties linked to the unique character of its project in Mount Morgan.

First of all, Carbine needs to address several types of regulations from the Queensland DEHP. Like any mining activity, Carbine is subject to requirements under the Mineral Resources Act 1989 (State of Queensland 2017c). However, its waste reprocessing activities also fall under the Waste Reduction and Recycling Act 2011 (State of Queensland 2017d). Additionally, because Mount Morgan is a site of historic value, Carbine is also concerned with cultural heritage protection matters. This level of legal requirements is affecting the progress of the project's development (Dann 2016, Hunter 2014).

Another difficulty in the negotiations between Carbine and the government is the question of royalties. Carbine is hoping to obtain royalty discounts, arguing that minerals are recovered from waste material generated by previous mining activities, and would be lost without Carbine's intervention (Dann 2016). Carbine straddles the line between mining and waste treatment, which then requires the government to adapt for this unusual business model.

Although this could provide a potential solution to the environmental legacies in Mount Morgan, the Queensland government is concerned about setting a precedent, which would encourage other companies to make the same demands, while not being certain of Carbine's future performance (Pegg 2016).

State governments may have sound reasons to exert caution, as some have experienced cases of mining companies using waste reprocessing as a pretext to defer dealing with the challenges of long-term waste management and environmental responsibility (Fawcett 2016).

7.2.4. Summary of case study findings

The main problems identified in the governmental involvement in Mount Morgan and Mount Lyell are the following:

- Need for more stringent regulations: although improvements have been made during the long mining history of the two states, the Queensland and Tasmania governments are still somewhat dependent on mining companies not attempting to close operations (or sell them or place them in care and maintenance) without completed and successful closure and rehabilitation. In particular, the case studies showed governments were unable to make companies accountable for the environmental damage they caused. The new Environmental Protection (Chain of Responsibility) Amendment Act as well as current efforts to improve financial assurance calculations have the potential to address these issues in the coming years. When it comes to un-mined economic resources, governments do not seem to have regulatory levers to motivate companies to complete extraction and maximise resource recovery.
- Inappropriate economic incentives: temporary loans and royalty discounts used by the government of Tasmania may have provided short-term help to prolong mining operations in Mount Lyell, however they seem to have only postponed the problem, while other government incentives could have potentially stimulated innovation within the company, and allowed it to find its own solutions. Besides, encouraging mining activities on one side, while not providing any economic support for a third party to treat the AMD, seems contradictory. This illustrates that the government departments are creating environmental and economic objectives that are in conflict.
- Lack of flexibility: given the past experiences between the government and the mining industry, it is understandable that both environmental protection and state development agencies developed a lack of trust for new mining companies that present an unusual business model, in particular those that claim to make value out of waste. However, innovation in mining practices needs to be supported by an open and flexible government, which needs to adopt more progressive approaches while maintaining the necessary safeguards to ensure properly protection for the environment.

7.3. Proposing policy changes

In her study of policy frameworks to support better practices in the oil and gas industry, Hunter (2014) prescribed a flexible policy framework built around overarching requirements. Flexibility is necessary to respond appropriately to new issues that extractive industries are facing, while overarching requirements or principles ensure the outcome does not deviate from certain objectives.

Improvements in mining legislation in Australia should be articulated around a central goal, which is to maximise the economic benefits of the exploitation of the nation's mineral resources in the long term (i.e. a matter of resource conservation) while minimising environmental and social impacts related to mining activities. For that, it is necessary to get a better understanding of the core challenges to achieve better sustainability outcome in the mining industry.

Chapter 2 reviewed the main sustainability frameworks applicable to the mining industry and concluded they currently had significant shortcomings. In particular, the ICMM's principles or the 7QS framework encourage users to embrace sustainability in its weak version, i.e. where the three pillars Economy – Environment – Social are considered separately and may conflict with each other (see 2.1.2.1). Determining an overarching goal for Australia's mining regulation framework offers the possibility to re-establish coherence and ensure mining policies are built on and derive from the concept of strong sustainability described in 2.1.2.1.

This thesis has explored the topic of the mining industry's contribution to sustainable development, in particular in Chapter 2, where two core challenges were highlighted:

1) the non-renewability of the mineral resource (2.1.2.2) - mining operations at the mine site level should aim at minimising waste of non-renewable resources,

2) the economic instability of mining operations (2.1.1.3) – notably the issue of premature closures.

Designing a regulatory framework that is articulated around a common goal to address these two challenges would first require quantitative and qualitative tools to set clear targets for improvement.

7.3.1. Managing non-renewable resources: criticality, mine site metabolism and waste management

- Criticality of minerals

Regarding the first challenge, policy-makers need to know how much can currently be achieved in terms of resource recovery, and how much wastage can be tolerated, and make use of this knowledge in the approval process of new mining projects. For a well-coordinated national strategy, and especially in the case of multi-metallic ore bodies (i.e. the question of by-products recovery), this requires knowing which minerals are the most important to recover. Previous studies have established priority lists based on the criticality of minerals. The methodology developed by Graedel, TE et al. (2012) proposes to assess the minerals' criticality over three dimensions:

- Supply risk: this includes geological, technological, economic, but also social and geopolitical potential future challenges in accessing and extracting a particular mineral. General declines in ore grades have contributed to increase supply risk for most metals;
- Vulnerability to supply restriction, i.e. how essential a particular mineral is to society, how high is the demand and whether it can be substituted or not;
- Environmental implications: this should also include significant local environmental problems. In the case of minerals causing AMD, this is an additional motivation for extracting them.

National and state governments can make use of such an approach to ensure that Australia's resources are managed in the longer term. This should be coupled with a different way of assessing productivity measures. Productivity is a ratio of output over input, and is meant to represent the efficiency of production (ABS 2016). Currently, the Australian Bureau of Statistics calculates multifactor productivity in the mining industry using labour and capital inputs, in monetary values (ABS 2015). It is also trialling a new definition of productivity that includes minerals and energy inputs, which should provide a more realistic estimate of the mining industry's performance. Productivity calculations could possibly be refined further by discounting the resource that is left behind, with a weighting factor that includes the minerals' criticality.

- Using the Material Flow Accounting (MFA) indicators

In addition to having a priority list based on currently known national resources, state governments could make use of MFA indicators to evaluate both a) the potential for prolonging the life of a mine and b) the performance of mining projects at the approval stage.

Regarding a), by using production data from past operations to calculate the MFA indicators, governments can evaluate the amount and the state of the resource left behind in waste or other material on site. Applying the indicators to a large number of mines – abandoned, closed, under care and maintenance, or currently operating - would establish a baseline to allow for comparison and provide an indication on the recoverability of remaining minerals. Results could be used as a preliminary assessment to determine whether it is worth investigating options for prolonging the mine by reprocessing waste, which would complement state level geological surveys that already provide some information on remaining primary resource.

Regarding b), calculating the MFA indicators using pre-feasibility or feasibility data would provide information on a future mining project's metabolism. For that, a database of current mining projects is necessary to allow for benchmarking and expectations from mining companies in terms of the efficiency of extraction. Criteria on acceptable amounts of resource left behind or mineral losses to waste can be determined.

A challenge in determining the MFA indicators early on in the mining project is that the exact composition of the ore body (or waste deposit in case of waste reprocessing projects) is not fully known. Therefore, an assessment using the MFA indicators may need a more dynamic modelling, with updates throughout the life of the mine.

- Recovery-oriented waste management

Waste management currently performed on mine sites needs to be improved for a longer-term and enhanced exploitation of the local mineral resource. The Mine Waste Management Hierarchy developed in Chapter 4, along with examples of technologies and practical applications, could constitute a basis for best practices guidelines to support mining companies.

However, information on best practices may not be sufficient for a recovery-oriented waste management system to be implemented in practice. It should be coupled with incentives to adopt preferably the two first levels of the hierarchy: waste prevention and reprocessing. Stricter disposal rules may constrain companies into seeking alternatives and potentially pursuing a more proactive waste management. It is also necessary to segregate waste material that does not yet qualify for reprocessing but could potentially qualify in the near future. New stockpiling designs that prevent all AMD for a given period of time (e.g. twenty years) should be sought (e.g. with an underneath membrane layer to collect leachate).

However, a recovery-oriented waste management implies longer time periods and could be compromised by the inherent instability of mining operations. This connects to the second challenge mentioned earlier.

7.3.2. Dealing with economic instability: resilience and continuity

Regarding this second challenge, which is interconnected with the first challenge since continued mining operations and consistent extractive strategies would ensure better resource efficiency and less resource sterilisation, the common goals for policies to build on would be:

- Avoiding interruptions in activities and premature closures: this is an issue of economic viability and poses the question of what could make a mining project more resilient to market changes (the question of resilience was raised in 2.1.2.3);
- Or alternatively, accepting interruptions and managing transition periods better: if susceptibility to fluctuating commodity prices is not avoidable, managing transitions better between two mining projects, could ensure a more consistent extractive strategy.

The drawbacks of interruptions and changes in ownership can be mitigated by an efficient transfer of knowledge. For a consistent waste management strategy, companies operating mine sites need to monitor waste amounts, location and composition, which could be provided to a potential future reprocessing company. This could be done using existing mechanisms such as the National Pollutant Inventory, which already requires mining companies in Australia to report their emissions and substances transfers to waste facilities (NPI 2012). This kind of reporting currently provides a classification of substances (e.g. the ‘copper and compounds’ category) which does not allow to quantify accurately the amounts of particular minerals of economic interest, and does not encompass non-polluting substances such as gold.

The Global Reporting Initiative is another world-wide reporting framework which could be strengthened, e.g. by including the MFA indicators. GRI indicators defined in the Sustainability Reporting Guidelines' supplement for the mining sector already prescribe to quantify and classify mine waste volumes and potential spillage, which would include AMD (GRI 2011). This provides information on bulk amounts of waste (volumes and weights), which connects with MFA indicators such as Net Waste Generation, but does not inform on the composition of these materials.

Increasing financial assurance and strengthening regulations to hold companies accountable for their environmental legacies and minerals resources left in-situ would incentivise them to meet their commitments and possibly seek alternatives initiatives to reduce environmental impacts and increase mineral recovery. However, that type of policy can result in further constraining mining activities rather than opening up the possibilities for innovation.

Regarding the more ambitious goal to avoid discontinuities in mining operations through more resilient business models, it is at present difficult to evaluate what these new models could be. To address this issue, governments can design policies with the aim of stimulating Research and Development (R&D) within the mining industry. The Porter hypothesis (Ambec et al. 2013) states that well-designed environmental regulations can make companies more competitive and innovative, e.g. by helping them to identify inefficient uses of costly resources. Although innovation is necessary for the industry to develop more resilient business models, the approach to innovation should be left to the industry, for it to find its own solutions. Ambec et al. (2013) suggest that training programs could be part of such a policy framework, and that well-defined property rights can ensure the most innovative companies do not get disadvantaged by sharing their innovations.

However, with fluctuating commodity prices it is likely that interruption periods in mining activities are unavoidable. On the other hand, premature closures and their multiple drawbacks may to be preventable. Well-explored regions experience fewer initial openings and final closings, while temporary closings and re-openings become more common (Slade 2001). Therefore, both regulators and mining companies need to adapt to mining regions becoming more mature, and it is possible for companies to plan for them and for governments to regulate these interruption periods. For that, governments should take into account the fact that the consequences of delaying re-openings and the costs of care and maintenance vary from one site to another, as the two case studies in Chapter 5 and 6 showed.

For mining companies, care and maintenance stages can be the opportunity to diversify their portfolio away from their core mining business, or to encourage a third party on site to perform waste reprocessing, water treatment or economic rehabilitation. The development of scavenger companies such as Carbine Resources and Raging Bull show an encouraging trend, which could be further supported by policy-makers. These existing alternatives to traditional mining businesses constitute some promising pathways for R&D in mining.

Overall, policy-makers may want to avoid setting policies that are too narrow and may interfere with the coherence of the larger system (Ehrenfeld 1994). Generally, Ehrenfeld (1994) calls for more holistic regulations, rather than regulations that are designed to solve a specific problem, arguing that a fragmented regulatory structure is less efficient. In the case of mining, narrow policies can for example result in failing to address possibly contradicting needs of rehabilitating versus prolonging the mine's life to increase resource recovery.

Finally, Ambec et al. (2013) also recommended designing regulations in a way that triggers continuous improvement, rather than for example prescribing a particular technology or certain emission limits. Setting solid standards results in companies not having incentives to go beyond compliance. This refers back to the notion of flexibility used by Hunter (2014).

7.4. Conclusion

Governments have a particular interest in maximising the value of their natural resources in the long term, as well as the authority to foster improved mining practices, and should therefore play a defining role in moving the mining industry towards a more sustainable management of the local resource.

Although there are some guidelines and mechanisms in place in Australia, the past and present involvement of the state governments in Mount Morgan and Mount Lyell show that there are still improvements to be made. The strengthening of environmental regulations that has occurred over the past decades, although beneficial in limiting irreversible mineral losses (through waste dumping and acid mine drainage), also generated additional constraints for mining companies. Policies that open up possibilities for reprocessing and reducing environmental impacts and/or legacies are a key part of the solution for sites such as Mount Morgan and Mount Lyell.

The government's involvement in Mount Morgan and Mount Lyell showed a disconnection between economic and environmental objectives. In designing new policies, it is important to recognise the interconnectedness between the environmental remediation and the economic instability challenges, and build legislation around a common goal to address them rather than considering them as two separate issues.

The example of Mount Morgan also exhibited a certain lack of adaptability from the government towards new business models. Adapting to and supporting projects such as Carbine Resources' is important for providing incentives for innovation in the area of waste reprocessing and economic rehabilitation. In Mount Lyell, Copper Mines of Tasmania holds a modern type of mining operation, yet it currently finds itself in an impasse. Stronger incentives for innovation may allow CMT to find solutions that are likely to lie outside of its core business.

Government could have a greater role in helping maximise the value of mineral resources. Firstly, governments could define objectives regarding the efficiency of mineral extraction at the mine site level (i.e. how much resource can be left behind at the end of a mining project) and use these core objectives to redefine their relationship with mining companies. These objectives or standards could be determined quantitatively using the MFA indicators. If applied to a large number of mining projects, the MFA indicators could be used to establish a benchmark, and would thus have the potential to inform governments on the relative performance of a mining project. This information could be used in the approval process, and updated throughout the life of the mining project as exploration and mining operations progress, and as the local resource, as well as the composition of the waste, become better known.

Secondly, dealing appropriately with the resource left behind as waste would require adopting the Mine Waste Management Hierarchy (MWMH) as part of best practices guidelines, which governments can help disseminate within the mining sector. The MWMH can be coupled with MFA results (e.g. by determining threshold concentrations above which reprocessing should be considered) to design a long-term waste management strategy that may go beyond the life of a single mining project and facilitate a potential future project.

Finally, for continuity and consistency in the local resource exploitation, a different approach to unavoidable interruptions in activities is needed. Although regulating mine closure and rehabilitation is important, regulating – or providing guidance on – temporary closures and care and maintenance periods becomes more relevant in mature mining regions. More guidance on temporary interruptions would also assist with mitigating the consequences of premature closures, allowing interruptions when they are needed and finding ways to cope with the resulting drop in revenues - e.g. by pursuing other non-mining related activities in the meantime.

8. Conclusions

This chapter summarises the main findings from this research for each chapter. It then assesses the contributions to knowledge, and makes recommendations for further research.

8.1. Summary of conclusions

Chapter 2 'Industrial ecology to improve mining sustainability frameworks'

A review of mining sustainability frameworks exhibited certain limitations of the most commonly used frameworks. Firstly, they tend to separate issues rather than integrate them in an overall implementable strategy. Secondly, they overlook considerations over the efficiency of extraction, which relate to a responsible exploitation of non-renewable resources, an aspect of sustainability that is specific to mining activities. Thirdly, the economic viability is also overlooked as if it were not a key aspect of sustainability. The lack of economic viability directly affects the efficiency of extraction, and may also have negative social and environmental impacts. This interconnection needs to be better understood in order to mitigate these adverse effects.

Chapter 2 then presented an overview of the field of industrial ecology, its main definitions and objectives as well as associated methods and tools. Industrial ecology applications to mining were reviewed and it was found that they were limited, and some authors raised methodological issues. In particular, one of industrial ecology's most commonly used analytical tools – life cycle analysis – is currently not well adapted to the variability of mineral deposits. However, the field's designs and capabilities offer significant opportunities to address the limitations of current mining sustainability frameworks.

Finally, findings from the literature review were used to provide a preliminary definition of the system under study in this thesis. The observation of flows and stocks of mineral resources at the mine site local level was found to be essential in order to counter the sustainability frameworks' limitations. Within these flows and stocks, particular attention should be paid to dissipative flows, in particular minerals lost in the waste stream, which are currently overlooked and poorly understood.

Chapter 3 'The Mine Waste Management Hierarchy'

Chapter 3 focused on mine waste management. Waste generation and composition are generally under-reported even though they can generate large environmental impacts. Some of these impacts are related to valuable minerals remaining in the waste, which may become mobile in the environment, and can cause significant detrimental environmental impacts.

This chapter highlighted that economic factors are critical in determining whether a mineralised material will be treated as waste or ore. A hierarchy for the management of mining waste – 'reduce, reprocess, downcycle, dispose' – was developed and explained by illustrating it with examples of existing mining practices as well as ongoing academic research.

For the highest level of the hierarchy, reduce and prevent waste, three main examples were given: avoiding high grading, developing pre-concentration methods, and maximising by-product recovery. The part on the second level of the hierarchy, reprocessing, provided examples of technologies used or currently being developed to reprocess mining waste, as well as particular circumstances that make reprocessing more attractive to mining companies. Backfilling is the most common example of downcycling, the third level of the hierarchy, followed by using waste as construction material. Finally, in the part on responsible disposal, the last level of the hierarchy, techniques of final disposal of reactive waste were compared against the need to stockpile for potential future reprocessing.

The last part of this chapter considered the hierarchy as a whole and argues that most successful waste management strategies would involve all levels of the hierarchy combined in the goal of maximising value creation and minimising waste-related environmental impacts. For this hierarchy to be implemented in practice, and in particular for waste reduction targets to be achieved, waste management needs to be well integrated within a mining project's extractive strategy and throughout the mine's life cycle.

Chapter 4 'Methodology development'

A three-dimension research methodology for the analysis of case studies was developed and presented in chapter 4. These three dimensions – the mining project, the mine's life cycle and the government’s role – all integrate the mine waste management system studied in chapter 3 and allow for a holistic perspective. The mine site – and the local mineral resource it contains – provides the geographical boundaries for this framework.

For the first dimension, a set of thirteen Material Flow Accounting indicators was developed in order to quantify the flows of minerals and mineralised material at the mine site level occurring during a particular mining project. They are meant to provide information on the mining project’s metabolism, notably by relating mineral losses to the particular practices that caused them.

The mining project needs to be distinguished from the mine’s life cycle, as more than one mining project may take place at different periods of the mine’s life. Taking a life cycle perspective allows for better understanding of the effects of events occurring between two mining projects or after the latest project on the same site. This raised the questions of how interruptions, changes in ownership, premature closures and site abandonments affect the coherence in the overall extractive strategy and the exploitation of the local mineral resource. A qualitative investigation was undertaken using both historical data to understand past practices, and data on the current situation to assess future opportunities for the remaining resource on site.

The third dimension observed mining operations in relationship with local governments, and how these external stakeholders have an influence on the mine’s life cycle and the exploitation of the local resource. The third dimension consisted of a qualitative investigation on the changes in governmental involvement, and how it influences resource recovery and mining practices, which allows for drawing conclusions on potentially beneficial changes in mining policies.

Chapter 5 ‘Case Study 1 – Mount Morgan, Queensland’

The life of the Mount Morgan mine can be divided into three main time periods that correspond to the three mining projects that took place: the historical operations (1882-1982), the Sandstone Gully tailings reprocessing project (1982-1990), and the abandonment of the mine followed by the arrival in 2015 of a new mining company Carbine Resources planning to reprocess waste material.

The Material Flow Accounting (MFA) indicator set presented in chapter 4 was applied to the three mining projects. The evolution of mining practices throughout Mount Morgan's life was thus measured in quantitative terms and the three projects compared. It appeared that the historical operations were advantaged by long lasting activities and high grades, however the two reprocessing projects benefit from having easily accessible material and having only a limited contribution to the site's environmental footprint. The Carbine Resources project would perform significantly better than the Sandstone Gully Tailings Reprocessing project according to the MFA results, due to higher recovery rates for major targeted metals and the recovery of by-products, including pyrite, the main mineral involved in Acid Mine Drainage reactions. This study concludes that waste reprocessing can, under certain circumstances, make a positive contribution to a mine site's sustainability credentials by recovering previously lost minerals and removing some of the acid generating material.

The discussion structured using the SWOT matrix concept (Strengths, Weaknesses, Opportunities, Threats) articulated the future opportunities for Mount Morgan regarding both the recovery of previously lost minerals and the site's environmental remediation. Opportunities are embodied in Carbine Resources' project, the material it targets for extraction and its proposed processing flowsheet (in particular the production of pyrite concentrate). However, for the project to have a significant contribution in addressing the environmental legacies of Mount Morgan, it will need to extend its mine plans further than what the pre-feasibility study forecasts. It is also crucial that Carbine builds a successful collaboration with the government, who has been the main stakeholder on site during the 27 years of abandonment. Therefore, although Carbine presents a promising plan, significant uncertainties remain as to whether Carbine will be able to make a positive contribution to mineral recovery and environmental remediation.

Chapter 6 'Case Study 2 – Mount Lyell, Tasmania'

The life of the Mount Lyell mine can be divided into two main time periods that correspond to the two mining projects that took place: the historical operations of the Mount Lyell Mining and Railway Company (MLMRC) (1888-1994), and the Copper Mines of Tasmania (CMT) project (1994-present).

Comparison between MLMRC and CMT results showed that differences between the two projects could be attributed to differences in size and duration, and to an improvement in waste management – i.e. the cessation of dumping practices and the containment of acid generating waste. Comparison between Mount Lyell and Mount Morgan showed that, because of past practices, mineral resource remaining on site in Mount Lyell is mostly found within the ore body, while at Mount Morgan it is mostly found in the waste material.

The study of Mount Lyell's history showed that waste dumping practices and high rates of Acid Mine Drainage caused by a wet climate conditions contributed to high irreversible mineral losses. Compared to Mount Morgan, there are considerably less opportunities for a resource recovery and remediation project to be economically feasible. Current mining activities are disengaged from any type of involvement in past environmental damage. CMT has contributed to recovering minerals left behind in the ore body by MLMRC's operations and is expected to continue in the future. However, it seems unlikely that they will manage to mine the remaining of the ore body. Although CMT is significantly increasing the life of the mine, CMT's contribution to waste minimisation, environmental remediation and resource recovery maximisation remains limited.

The chapter concludes related to the applicability of the developed set of MFA indicators. It was found that comparison between different mine sites would require the set to be applied to a broader sample of sites in order to establish a baseline and allow for a more absolute assessment of a mine's performance. In addition, to improve comparison across different mines and commodities, mineral values should be aggregated using weighing factors other than fixed unit prices.

Chapter 7 'Policy incentives for a more sustainable management of mineral resources'

Chapter 7 discussed how governments have both an interest in and the authority to regulate mining operations in a way that favours a more sustainable exploitation of the local resource for the long-term conservation of the national resource. The role of governments in this area is therefore paramount.

Although some guidelines and procedures exist at the national and state level to address the issue, observations of government involvement in the two case studies showed that it still lacks a certain control over the mining operations once they have started. In particular, state governments were not successful in preventing or mitigating the drawbacks of premature closures. Besides, they had a tendency to deal with economic incentives for prolongation of mining activities and the enforcement of environmental requirements as two separate issues.

The chapter concluded with a discussion on potential improvements to the current Australian mining policy. Overall, the essential goal for governments is to stimulate innovation within the mining industry in a way that the industry finds itself the solutions to its economic viability and efficiency issues. Industrial ecology prescribes the use of procedural methods to implement solutions into practice. MFA indicators can be used as part of a national or state level regulatory framework to assess past, current and future mining projects. Applying the MFA indicators to a large number of sites would allow for establishing a baseline to support decision-making. In particular, future projects could be assessed regarding the efficiency of their extraction strategy, and prioritised at the approval level. Waste management strategies adapted to the estimated mineral content of the waste could be prescribed early on.

Updating best practices guidelines to include the Mine Waste Management Hierarchy would exhibit ways to make value out of mining waste and stimulate innovation in this direction. In return, the government should encourage new business models that explore ways to create value from mining waste and enhance mine sites' environmental remediation.

8.2. Contributions to knowledge

The main contribution to knowledge of this thesis is the application of an industrial ecology approach to the mining industry. Industrial ecology, as a concept, compels the practitioner to view waste as a potential resource. As a field of research, it allows analysing material flows and modelling a mine's internal metabolism. It also invites to observe the influence of political and regulatory factors on this metabolism. This thesis investigated the characteristics and the potential of a preventive, recovery-oriented approach to mine waste management in the metal mining sector. Industrial ecology has historically been focused further down the value chain and applications to the mining industry are still rare. This thesis established basic principles and identifies key challenges for this particular sector, which should be the basis for further research work in this area.

Three key outcomes of the thesis are the following:

- The Mine Waste Management Hierarchy: this thesis brings a new perspective on mining waste, which can be considered as a potential resource whose value may be unlocked now or in the future, rather than an environmental and economic burden. The new hierarchy of practices for the management of mineralised mining waste was developed from this alternative view point and illustrated with practical examples;
- The MFA indicators: these indicators were developed to evaluate the metabolism of a mine site, identify and quantify sources of mineral losses, as well as benefits of enhanced resource recovery. Material flow analysis frameworks have been previously applied at the scale of countries, regions and industrial areas, but not to mine sites. This research adapts the methodology to focus on flows of mineralised material – bulk amounts and mineral content – that characterise the core level of a mine's metabolism;
- Policy incentives: the local exploitation of mineral resources needs to be integrated within regional, national and global strategy for the conservation of non-renewable resources, as part of sustainable development goals. Governments are key players in this area. Through the case studies, this thesis analyses the repercussions of political decisions and regulatory changes on mining practices, and makes recommendations for improving the government's involvement. This provides new approaches for governments to contribute and influence a positive change in mining practices.

These three outcomes as well as other secondary outputs of the thesis are summarised in figure 8.1.

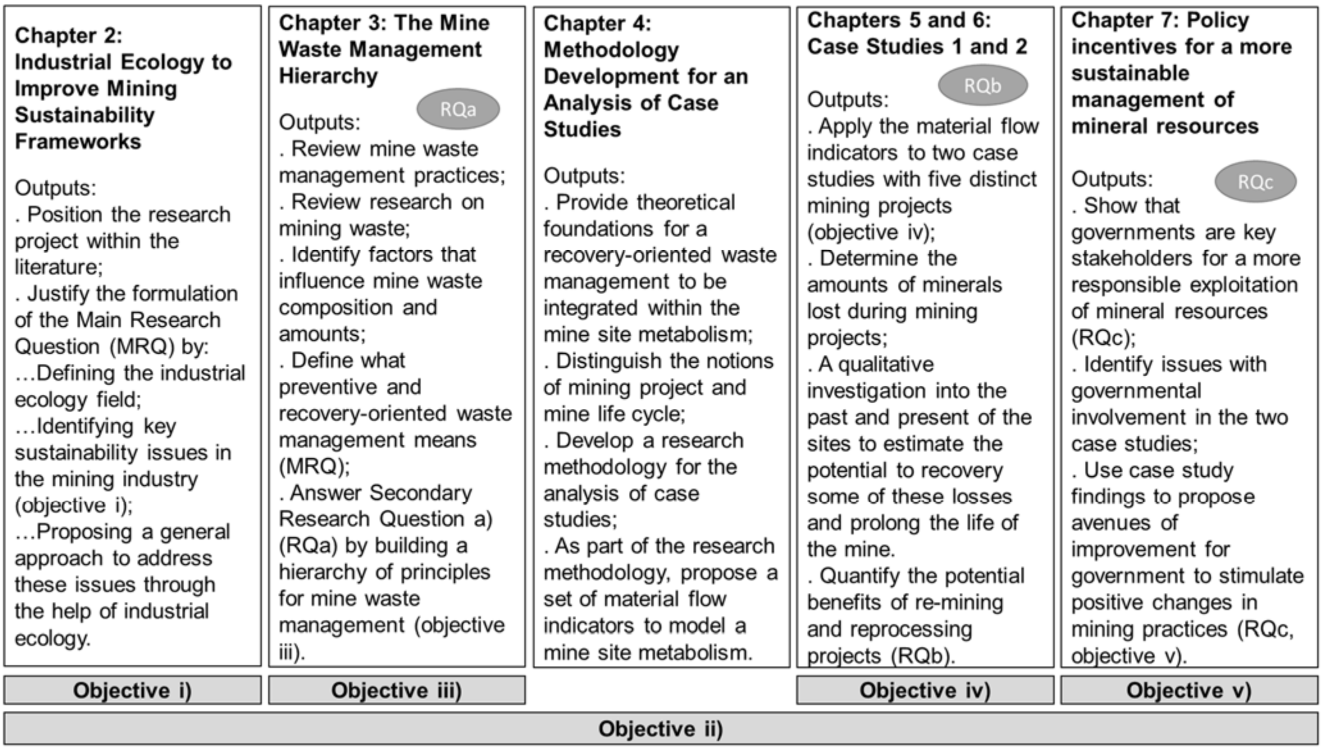

Figure 8.1: Thesis outputs per Chapter and their connection with objectives and research questions as defined in section 1.2

This thesis initially asked, as the main research question:

How could a preventive, recovery-oriented mine waste management system based on the concept of industrial ecology, which would view waste as a potential future resource, contribute to improving the sustainability credentials of a metal mine?

To answer this question, this thesis has first attempted to determine the main characteristics of such a mine waste management system. It has observed mining practices and evaluated the extent to which they aligned with an ideal case where mineral losses are minimised and the life of mine is maximised. The analysis of case studies identified the sources of mineral losses, and evaluated those that could have potentially been prevented. Finally, the thesis highlighted the role of governments as key stakeholders whose interest align with a long-term responsible exploitation of mineral resources. This study concludes with possible policy incentives to influence mining practices. Together, the waste management perspective, the life cycle perspective, and the policy perspective taken in this thesis aim at contributing to sustainable development. More specifically, if applied, the recommendations made throughout the thesis would contribute to “improving the sustainability credentials of a metal mine” by minimising losses of non-renewable resources and minimising the environmental impacts associated with mine waste disposal.

Finally, this thesis also contributes to knowledge through the case study findings. The information collected and analysed during and after the fieldworks contributes to better transparency on past and current mining practices, which are generally unknown to researchers outside of the mining field. This perspective into the reality of mining operations is crucial for academic research to go beyond theoretical considerations and help find concrete solutions to the industry's challenges.

8.3. Recommendations for further research

Several topics for potential future research were identified during the course of this thesis, and are grouped into two key areas:

- Recommendations for potential future users of the case studies methodology to enhance its quality and applicability;
- General recommendations for future research in this field, for both industrial ecologists working in related areas, and research on sustainability frameworks for the mining industry.

8.3.1. Improvements to the methodology for the case studies and its application

Improvements to the framework would achieve for more and better quality data, which would require engagement with and cooperation from the mining industry, and include:

- More detailed data on the case studies to improve MFA indicator results. In particular, relevant data missing were the concentrations of potential by-products within the ore or waste material, e.g. silver in Mount Morgan, and pyrite, zinc or cobalt in Mount Lyell. It is possible that some of this data could have been available from the companies on site, however, much of it did not exist. For various reasons such as cost or not part of core business, past companies may have chosen not to recover some by products, or mine parts of the deposit considered to be uneconomic or reprocess waste material that are thought to be uneconomic. As result this data are not readily available.

- In addition, while the MFA results in Mount Morgan and Mount Lyell are useful in understanding better the metabolism of a mine site, applying the indicators to a larger number of sites would allow for quantifying the relative performance of a particular site. Establishing a baseline with mines of various sizes and locations, and producing different commodities would allow for comparing sites that are similar, and estimate the potential for improvement. Examining more mines would also allow for comparing mines of similar life time, and observing the influence of technological innovations. It is likely that some of the indicators would present significantly different values depending on the time period or on specific site characteristics. While the comparisons between Mount Morgan and Mount Lyell as well as between two mining projects from the same site provided a useful analysis in meeting the objective of this thesis, a greater repository of values of MFA indicators from different sites would enhance the overall assessment of economic and environmental potential.
- For a more complete understanding of a mine site's metabolism, one would need to have data on energy consumption as well as other external resources (water, land, chemicals, other metals embedded in infrastructure etc.). Such data could be used in a Life Cycle Assessment-type of framework where both direct and indirect resource uses are taken into account (e.g. Rönnlund et al. 2016a). Alternatively, this information could be added to the existing MFA framework with additional indicators, such as the ones presented in section 4.2.3 titled 'additional relevant indicators. For an even more holistic approach, it would be also worth encompassing the social impacts of mining (e.g. need for resettlement, investment in public infrastructure, job creation etc.).
- The MFA indicators expressed in monetary units provide information on the revenues of the mining project. Adding cost-related indicators (e.g. capital cost and operating cost) to the MFA set would allow identifying the conditions in which a waste reprocessing project can be economically profitable.
- As mentioned in 7.3.1, criticality considerations could be included as a weighing factor when aggregating several metals or minerals together. This would contribute to complete the baseline by defining which minerals should be prioritised for extraction. This is particularly informative for policy-making.
- Finally, the policy perspective could be enriched with interviews with both government, industry and other key stakeholder representatives. This would provide

further information on the way the government's role is perceived by both stakeholders.

8.3.2. Recommendations for future research

This thesis covered the largely unexplored area of the intersection between the fields of industrial ecology and mineral resource exploitation. There are substantial benefits in bridging the two disciplines, as industrial ecology can drive a different thinking for solving problems related to mine waste management, for mutual benefits. Significant research efforts are still needed in this area, from both sides of the research gap. Recommendations for the future are the following:

- On the mineral resource exploitation side, greater levels of innovation in mine planning are necessary. Using the mine lease as system boundaries, an industrial system analysis would assess ways of integrating a proactive and value maximising approach to mine waste management within mining operations. This type of systemic research would be likely to bring more successful and deeper changes than research focused on improvements on one part of the mine e.g. new technologies. Past examples such as the work of Struthers (1999) are rare.
- Still on the mining side, further research could study the potential for industrial collaboration at the mine site level. The example of Mount Lyell shows an attempt to attract a third party to treat the acid mine drainage. In the Century zinc mine in Queensland, MMG sold the mine to the Century Mine Rehabilitation Project, which would re-process MMG's tailings and perform 'economic rehabilitation' (Barry 2017). Such projects could start before the end of previous mining activities, allowing a new company with a different expertise on site. Industrial symbiosis was considered as part of the review of IE modelling tools in Chapter 2. Opportunities for new business models should be explored by notably observing existing case studies possibly outside of Australia, e.g. Coniston industrial park in Canada (City of Greater Sudbury non dated). The concept of industrial symbiosis and industrial collaboration also provides an incentive to explore currently overlooked opportunities for the recovery of by-products within or surrounding the orebody.
- On the industrial ecology side, improvements to global metal cycles need to encompass the mining and mineral processing stages, situated at the beginning of all metal-containing products' value chains. The connection between mineral and

metallurgical processing needs to be studied further, as the composition of the intermediate product – the mineral concentrate – is related to processing recovery rates both upstream and downstream. Losses could be minimised as a result of optimisation between the two sectors. Within the industrial ecology field, further research may also be dedicated to strengthening Life Cycle Assessment applications to mining. Although limitations to using Life Cycle Assessment were raised in Chapter 2, it remains the most used industrial ecology tool and sustainability assessment of mining activities would benefit from a more standardised and official tool.

- Finally, significant work can be added on the policy and regulation side, exploring further the different types of governmental involvement in mining activities, comparing different legislations and their effectiveness around the world.

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9. Appendix I

Details of Material Flow Accounting (MFA) calculations for Mount Morgan

Two different publications Wels, Findlater and McCombe (2006) and Mudd (2009) provided estimates for the bulk amounts of the two main types of mine waste present on site, tailings and waste rock. Table 9.1 gathers these estimations and deduces assumed tonnages of tailings and waste rock, which are used for the calculation of the Net Waste Generation indicator for the historical operations.

Table 9.1: Waste generation for historical operations

	Source: Wels, Findlater and McCombe (2006)
Name of waste deposit	**Estimated amount (Mt)**
Horse Paddock Dump (waste rock)	15
Airfield Dump (waste rock)	24
Western Dump (waste rock)	25
Shepherds Dump (waste rock)	21
B&K Dumps and others (waste rock)	8.4
Open cut and Sandstone Gully tailings	28
Mundic Red Tailings	0.63
Mundic Grey Tailings	0.97
No.2 Mill Tailings	2.1
Shepherds Tailings	3.9
Total tailings generation*	35.6
Total waste rock generation	93.4
	Source: Mudd (2009)
Total tailings generation*	49.7
Total waste rock generation	95.5
	Assumed amounts for MFA calculations
Total tailings generation	**40**
Total waste rock generation	**90**

* Significant difference in tailings amounts may be explained by the fact that Mudd (2009) is taking into account all tailings generated, whereas Wels et al. (2006) is estimating the

amount of tailings present on site, therefore excluding tailings dumped in the river in the early years of operations

Table 9.2 gathers production values for all three mining projects, as well as assumed prices for all extracted commodities. These numbers are used to calculate the Total Production indicator. Table 9.3 provides the results of exploration studies from Carbine Resources, which estimated the mineral content of potentially minable waste. These figures were used to estimate Total Mineral Losses to Waste by the historical operations and the STR project.

Table 9.2: Production calculations for the three mining projects. Source for commodity prices: Carbine Resources (2015).

		Production			
	Prices (US$/t)	**Historical operations**	**STR project**	**Carbine Resources**	**Unit**
Copper	5,100	400,000	0	0	t
Gold*	36,200,000	225	14	9	t
Silver	590,000	50	4.5	0	t
Copper sulphate	1,750	0	0	40,000	t
Pyrite concentrate	60	0	0	2,000,000	t
Total production		**10,200**	**510**	**520**	**M$**

* 1 oz = 0.00003110 t

Table 9.3: Previous operations mineral losses to waste according to Carbine Resources exploration programme. Source: Carbine Resources (2015).

		Average grades		Average amounts*	
	kt	Au (g/t)	Cu (%)	Au (t)**	Cu (t)
JORC resources	8,348	1.23	0.15	10	12,300
Exploration targets:					
Other tailings	3,090	1.56	0.16	5	5,000
Mullock dumps	2,125	1.85	0.13	4	3,000
Metallurgical Slag	3,925	0.80	0.56	4	24,500
Open pit tails	26,650	0.53	0.09	14	24,000

* All figures were calculated by taking the average of the low range and high range values.

** 1 oz = 0.00003110 t

Table 9.4 shows that the percentage of waste explored by Carbine and therefore the percentage of waste included in the calculations of Total Mineral Losses to Waste is of about 34%, which means TMLW and other derived indicators are underestimated.

Table 9.4: Comparison between Carbine Resources' JORC resources and exploration targets and actual amounts of waste on site

JORC resources	8	Mt
Total JORC resources and exploration target	44	Mt
Total waste on site	130	Mt
Percentage of waste classified as JORC	6	%
Percentage of waste explored	34	%

Table 9.5 provides details on the calculations of Mineral Losses to New Waste, Total Mineral Losses to Waste, and Extraction Inefficiency indicators for all three mining projects. Note that silver recovery rates were unavailable for all three operations, and therefore, silver was not included in the MLNW. It is expected that this does not affect the results much as silver represents only a small part of revenues in the past operations: 1% of the revenue during the STR operations, and 0.3% during the historic operations.

Table 9.5: Mineral Losses to New Waste, Total Mineral Losses to Waste, and Extraction Inefficiency calculations. Sources: Carbine Resources (2015) and Findlay (2015).

	Historical operations*	**STR project**	**Carbine Resources**
Au losses (t)	51	14	2.8
Au recovery rates (%)	Not Available	50	76
Cu losses (t)	68,800	24,000	4,700
Cu recovery rates (%)	Not Available	0	68
Pyrite con. losses (t)**	35,000,000	7,600,000	220,000
Pyrite recovery rates (%)	0	0	90
Mineral Losses to New Waste (M$)	**4,300**	**1,100**	**140**
Total Mineral Losses to Waste (M$)	**4,300**	**590**	**-380**
Extraction inefficiency (%)	**30**	**68**	**21**

* Gold and copper losses during historical operations were estimated using Carbine Resources exploration results, knowing that these only cover 34% of all waste on site. Hence, these numbers are likely to be underestimated.
** Pyrite grades are not available. For both the historical operations and the STR project, it was therefore assumed homogenous pyrite concentrations in all waste material. Pyrite concentrate losses were then determined using Carbine's expected pyrite concentrate production and recovery rate.

Table 9.6 provides calculations for the estimation of Irreversible Mineral Losses through Acid Mine Drainage (IML-AMD) for a 20-year period assuming steady state is achieved. AMD water composition was estimated from the results of open pit water samples performed in 2014 (LPSDP 2015).

Table 9.6: Estimation of mineral losses in AMD over the 1995-2015 period

Total AMD seepage flow not intercepted*	3	L/s
AMD water volume for a 20 year period	1900000	m3
Sulphur concentration	5560	mg/L
Copper concentration	79.3	mg/L
Sulphur amount lost in a 20 year period	10000	t
Copper amount lost in a 20 year period	150	t
Value of sulphur lost (in pyrite concentrate equivalent)**	0.72	M$
Value of copper lost	0.8	M$
IML-AMD	1.5	M$

* According to Wels, Findlater and McCombe (2006), the seepage interception system in place in Mount Morgan intercepts about 82% of all AMD flow, which is then redirected back to the open pit.

** The value of a tonne of sulphur was determined using the value of 60 US$/t of pyrite concentrate with 50% sulphur content (Carbine Resouces 2015).

Table 9.7 gathers information on the tailings deposits selected for re-mining by Carbine Resources, according to its prefeasibility study. Knowing historical data including the age of the deposits allows drawing initial hypotheses as to the potential composition of the deposits and the recoverability of contained minerals.

Table 9.7: History of tailings disposal in Mount Morgan (Findlay 2015)

Deposit name	Time period	Comments
Red Oxide tailings	Late 1800's - early 1900's	Subsequently covered with metallurgical slag
Mundic tailings	1920s – Late 1950s	Deposited in several dams up the length of the gully
No 2 tailings dam	1938 – 1960	Progressive expansion, impoundment built up in two lifts over the original dam wall
Sandstone Gully pit	Late 1940s – unknown	
Shepherd tailings dam	Early 1970s - 1982	After 1979 tailings from Mt Chalmers ore processing were also deposited there. They are known to have higher copper grades.

Table 9.8 gathers the MFA results as presented in Chapter 5, Table 5.3, with an added column that corresponds to the results for the entire life of Mount Morgan. This allows visualising the contribution each project makes to the entire life of the mine. In particular, the difference between the Mount Morgan and the historical operations figures corresponds to the contribution of the two waste reprocessing projects.

Table 9.8: MFA results for Mount Morgan

	Historical operations	**STR Project**	**Carbine Resources**	**Mount Morgan Total**
Years of operation	100	8	8	116
Total Production (TP) (M$)*	10,200	510	520	11,200
Annual Production (AP) (M$/year)	102	64	65	97
Total Production from Waste (TPW) (M$)	0	510	520	1,030
Total Material Processed (TMP) (Mt)	50	28	8	86
Material Processed Annually	0.5	3.5	1	0.74

(MPA) (Mt/yr)				
Total Material Moved (TMM) (Mt)	140	28	14.6	183
Material Moved Annually (MMA) (Mt/yr)	1.4	3.5	1.8	1.6
Net Waste Generation (NWG) (Mt)	130	0	-2	128
Material efficiency (ME) ($/t)	73	18	35	62
Mineral Losses to New Waste (MLNW) (M$)	4,300	1,100	140	Not Applicable
Total Mineral Losses to Waste (TMLW) (M$)	4,300	590	-380	3,300
Extraction Inefficiency (EI) (%)	30	68	21	23
New Area Impacted (NAI) (Ha)	270	0	0	270

* Monetary unit used for all MFA calculations is US$.

In observing the contribution of the two waste reprocessing projects to the life of the mine, it is relevant to highlight the evolution of the Material Efficiency (ME) and Extraction Inefficiency (EI) indicators between the end of the historical operations and the potential end of Carbine's operations. The ME decreases from 73 US$/t to 62 US$/t, which is due to the fact that both waste reprocessing projects have a low efficiency in terms of the economic value they generate per unit of material moved (mainly because of lower grades). However, this decrease is relatively small if compared to the two projects' MEs (18 US$/t and 35 US$/t).

On the other hand, the EI decreases from 30% to 23%, which shows the waste reprocessing projects have a significant positive impact on the overall resource recovery of the mine.

10. Appendix II

Details of Material Flow Accounting (MFA) calculations for Mount Lyell

Table 10.1 gathers historical data on the main open cut and underground mines in Mount Lyell, the amount of ore mined from each deposits, average grades, date of mining and geological information when available.

Table 10.1: Main open cut and underground mines in Mount Lyell, from oldest to most recent. Source: Newnham (1993) and Bottrill (2001)

	Type of mining	Ore (Mt)	%Cu	g/t Ag	g/t Au	Date and type of ore
Iron Blow	Open cut	5.6	1.29	61.22	1.99	1883 – 1929: pyrite-rich bodies
North Lyell	Open cut and underground	4.7	5.28	34.29	0.4	1896 – 1972: Higher grade bornite-rich ores
Royal Tharsis (West Lyell)	Underground	2	1.56	2.77	0.49	1902 - 1991
Lyell Comstock	Open cut	1.3	2.38	5.23	0.67	1913 - 1959
Crown Lyell (North Lyell)	Open cut	4	1.62	6.67	0.37	1931 – 1985: Banded, thin pyrite lenses
West Lyell Open Cut	Open cut	58.3	0.72	1.66	0.25	1934 - 1978
Cape Horn	Open cut	4.1	1.43	3.3	0.42	1969 - 1987
Prince Lyell (West Lyell)	Underground	28.5	1.29	2.91	0.4	1969 -1995: low to moderate-grade chalcopyrite and pyrite
Razorback (West Lyell)	*Underground*	*0.2*	*1.1*	*1.48*	*0.24*	*Unknown*
Lyell Tharsis (North Lyell)	*Open cut*	*0.7*	*0.94*	*4.85*	*0.27*	*Unknown*
Others		*0.2*				

Table 10.2 provides details on the calculations of Total Production for both mining projects. Production figures are first expressed in kilo-tonnes for each commodity, then translated in

US$ million using the same commodity prices as for the Mount Morgan case study, then aggregated to one figure for the TP indicator.

Table 10.2: Production calculations for the two mining projects. Source: Mudd (2009) for copper, gold and silver production, and Newnham (1993) for pyrite concentrate production. Commodity prices are assumed the same as in Mount Morgan (Carbine Resources 2015).

		Production (kt)		Production (M$)	
		MLMRC	CMT	MLMRC	CMT
	Price (US$/t)	1888-1994	1995-2012	1888-1994	1995-2012
Copper	5,100	1,220	450	6,200	2,300
Gold	36,000,000	0.033	0.0084	1,200	300
Silver	590,000	0.61	0.064	360	38
Pyrite Concentrate	58*	430	0	25	0
Total production				**7,800**	**2,600**

* Pyrite concentrate produced in Mount Lyell had a 48% sulphur content, while Carbine Resources' pyrite concentrate would have a 50% sulphur content. Therefore, prices were modified proportionally.

Table 10.3 provides details on the calculation of mineral losses to tailings, which are used later to estimate Total Mineral Losses to Waste, for both mining project. Mineral losses to tailings were calculated using annual production numbers from Mudd (2009) and constant recovery rates. Recovery rates for CMT were provided by Cordery (2016); copper recovery rates for MLMRC were assumed using global estimations from Hatayama, Tahara and Daigo (2015); gold and silver recovery rates for MLMRC were assumed similar to CMT.

Table 10.3: Mineral losses to tailings (Cordery 2016; Hatayama, Tahara and Daigo 2015; Mudd 2009).

	Recovery rates (%)		Losses to tailings (t)		Losses to tailings (M$)	
	MLMRC	CMT*	MLMRC	CMT	MLMRC	CMT
Copper	0.85	0.92	180,000	39,000	920	200
Gold	0.65	0.65	18	4.5	650	160
Silver	0.62	0.62	360	39	210	23
Pyrite con.**	Unknown	0	12,000,000	4,100,000	720	250
Total mineral losses to tailings					**2,500**	**630**

* According to Cordery (2016), technical improvements have been implemented at the beginning of CMT operations, resulting in higher recovery rates for copper.
** Amounts of pyrite concentrate. According to Cordery (2016), sulphur content in waste material can be assumed to be of 5.3%. Amounts are multiplied by two to match Carbine Resources' pyrite concentrate of 50% sulphur content.

Mineral losses to waste rock are the second component necessary to estimate Total Mineral Losses to Waste. Calculations are presented in Table 10.4. Lack of data required a number of assumptions gathered below the table, which results in higher uncertainty.

Table 10.4: Mineral losses to waste rock. No data was available on the amount of pyrite in waste rock, therefore pyrite is not included in the calculations and losses may be underestimated.

	Waste rock grades		Losses to waste rock (t)		Losses to waste rock (M$)	
	MLMRC	CMT	MLMRC	CMT	MLMRC	CMT
Copper*	0.17%	0.50%	77,000	5,000	390	25
Gold	0.00045 g/t**	0.15 g/t	Negligible	0.15	Negligible	5.4
Silver	0.0066 g/t**	2.19 g/t	Negligible	2.19	Negligible	1.3
Total losses to waste rock					**390**	**32**

*According to Newnham (1993), MLMRC's waste dumps are estimated to contain 45 million tonnes of 0.17% copper. These estimations take into account the West Lyell dump only, hence results may be underestimated.
** Average grades for gold and silver in waste rock were estimated using annual ore grades collected by Mudd (2009). The difference between ore grades and waste rock grades for gold and silver were assumed to be proportional to the differences for copper grades. Results of these calculations provided losses to waste rock in dollars that were about 10^3 times lower than copper values, hence gold and silver amounts were assumed to be negligible.

Table 10.5 estimates Irreversible Mineral Losses through Acid Mine Drainage for a 20-year period, assuming steady state was reached. Results do not include gold and silver content as they are not considered as contaminants and therefore not reported. Past AMD data was not available.

Table 10.5: Irreversible Mineral Losses through Acid Mine Drainage, estimated for the 1995-2015 period. Source: Koehnken (1997).

	Flow (L/s)	Copper (ppm)	SO4 (ppm)	Volume (m3 in 20 years)	Copper (t)	SO4 (t)
West Lyell waste dump	54	82	6,430	34,000,000	2,800	220,000
West Lyell tunnel	4	14	2,100	2,500,000	35	5,300
North Lyell tunnel	56	54	1,655	35,000,000	1,900	58,000
Conveyor tunnel	92	134	3,995	58,000,000	7,800	230,000
Magazine creek	19	22	4,133	12,000,000	260	50,000
Total amount (t)					13,000	560,000
IML-AMD (M$)					66	13*
					79	
Total amount (t) - Other source : Euralba Mining (1992)**					16,000	not estimated
Total amount (t) - Other source : Taylor (1996)**					7,300	219,000

* The value of a tonne of SO4 was determined using the value of 60 US$/t of pyrite concentrate with 50% sulphur content (Carbine Resouces 2015).
** Amounts calculated from other sources provide the same order of magnitude. Lower values found in Taylor (1996) can be explained by the fact that the sampling is performed in the downstream river, whereas sampling in Koehnken (1997) is done at the source.

Table 10.6 provides an estimation of the Resource Left Behind (RLB) in Mount Lyell’s ore bodies. Data originates from the Geological Survey of Tasmania (2016). Dataset does not include silver and pyrite, which are therefore not included in RLB indicator. Data is updated to 31/03/2016, that is to say during CMT's care and maintenance period, and therefore represents CMT's RLB. MLMRC's RLB can be calculated by adding CMT's production to CMT's RLB. Measured and indicated resources amount to a total of 29.9 Mt.

Table 10.6: Resource Left Behind. Source: Geological Survey Tasmania (2016).

	Grade	Tonnage (t)	Value (M$)
Copper	1.08%	323,000	1,650
Gold	0.31 g/t	9.3	330
RLB by CMT		29,900,000	**1,980**

Finally, Table 10.7 provides the total MFA results as presented in chapter 6, with an added column for the entire life of Mount Lyell, and with added comments on the data sources as well as on the way individual indicators were calculated.

Regarding the entire life of mine results, the evolution of the Material Efficiency (ME) and Extraction Inefficiency (EI) indicators before and after CMT can be observed. ME raises slightly from 47 US$/t to 50 US$/t due to improved mining practices from CMT. A more significant change however is observed for EI, which decreases from 49% to 35%, even though CMT's EI is of 50%. This is because CMT contributes to prolonging mining operations and increasing mineral recovery from the site, thus benefiting the overall mine's efficiency of extraction.

Table 10.7: Mount Lyell MFA results with comments

	MLMRC 1888-1994	CMT 1995-2012	Mount Lyell Total	Comment
Years of operation	106	18	124	Source: Mudd (2009)
Total Production (M$)*	7,800	2,600	10,400	Source: Mudd (2009)
Annual Production (M$/year)	74	144	84	
Total Production from Waste TPW (M$)	0	0	0	No record found of waste reprocessing
Total Material Processed TMP (Mt)	112	39	151	Source: Mudd (2009)
Material	1.1	2.2	1.2	

Processed Annually (Mt/yr)				
Waste Rock Generation (Mt)	55	1	56	Source: Cordery (2016). Mudd (2009) estimated 44 Mt of waste rock for MLMRC, however this may be underestimated due to lack of reporting on MLMRC's side
Tailings Generation (Mt)	111	39	150	Source: Mudd (2009)
Total Material Moved (Mt)	167	40	207	TMM = TMP + waste rock generation
Material Moved Annually (Mt/yr)	1.6	2.2	1.7	
Net Waste Generation (Mt)	166	40	206	
Material Efficiency ($/t)	47	65	50	
Total Mineral Losses to Waste (M$)	2,900	660	3,560	TMLW = losses to tailings + losses to waste rock
Mineral Losses to New Waste (M$)	2,900	660	3,560	MLNW = TMLW as no waste reprocessing activity
Irreversible Mineral Losses through dumping (M$)	2,500	0	2,500	IML-D = MLMRC's losses to tailings
Irreversible Mineral Losses through AMD (M$)	76.6	2.4	79	IML-AMD = 79 M$ was estimated for the 1995-2015 period where steady state is assumed. The Mount Lyell Acid Mine Drainage Reduction Act (State of Tasmania 2003) attributes the responsibility of 3% of total AMD generation to CMT
Resource left behind (excl.	4,600	1,980	1,980	RLB by MLMRC = RLB by CMT + TP of CMT

waste) (M$)				
Extraction Inefficiency (%)	49	50	35	EI = (TMLW+RLB)/(TMLW+RLB+TP)
New Area Impacted (Ha)	2,800	246	3,000	Source: Cordery (2016). NAI of CMT is equal to the size of CMT's tailings storage facility, which was built outside of the site's historical mining lease.

* Monetary unit used for all MFA calculations is US$.